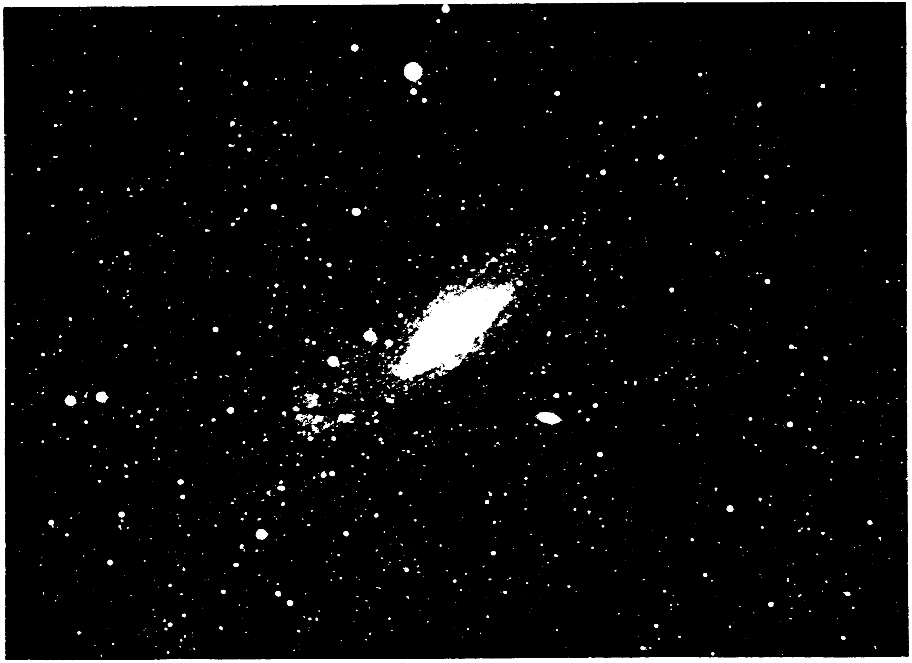
MODERN COSMOLOGIES

By the same Author

MODERN ASTRONOMY: Its Rise and Progress.

THE CHURCH AND SCIENCE

THE ROMANCE OF MODERN ASTRONOMY



The Great Nebula (M 31) in Andromeda

MODERN COSMOLOGIES

A HISTORICAL SKETCH OF RESEARCHES AND THEORIES CONCERNING THE STRUCTURE OF THE UNIVERSE

By

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OXFORD UNIVERSITY PRESS

LONDON: HUMPHREY MILFORD

1929

OXFORD UNIVERSITY PRESS
AMEN HOUSE, E.C. 4
LONDON EDINBURGH GLASGOW
LEIPZIG NEW YORK TORONTO
MELBOURNE CAPETOWN BOMBAY
CALCUTTA MADRAS SHANGHAI
HUMPHREY MILFORD
PUBLISHER TO THE
UNIVERSITY

Printed in Great Britain

PREFACE

THIS little book consists of eight lectures delivered under the 'David Elder' foundation in the Royal Technical College, Glasgow, during the winter of 1928–9. With a few alterations they now appear substantially as originally delivered.

The book is published in the hope that it may prove to be a useful summary of observations and theories bearing on the problem of cosmology—the all-inclusive problem of modern astronomy. In the lecture on Herschel's work I give reasons for dissenting from Proctor's opinion that the great astronomer abandoned the disc-theory in the course of his observing career. My own study of Herschel's papers has convinced me that while Herschel modified considerably the assumptions underlying it, he certainly did not abandon the concept of the Universe as a thin flat disc, greatly extended in the plane of the Milky Way.

I am much indebted to the well-known astronomer, Mr. Peter Doig, F.R.A.S., for his kindness in reading over the manuscript and for several valuable corrections and suggestions.

H. M.

EDINBURGH,
July 1929.

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THE GEOCENTRIC COSMOLOGY

THE history of cosmological thought has been the story of the progressive recession of the centre of the Universe from the world on which we live. Cosmological theories did not even begin to approximate to the truth until Copernicus dethroned the Earth from the central place which had been attributed to it.

The pre-Copernican cosmologies, which need not long detain us, may be divided into three groups—the mythological, the philosophical, and the scientific. The ancient peoples of antiquity—such as the Assyrians, Babylonians, Egyptians and Hebrews, and the Greeks before the time of Thales—each had their own world-view, in which cosmology and theology, cosmogony and theogony were indissolubly intertwined. So long as nature was regarded as full of warring deities, so long as men recognized no world-order, the formulation of any kind of cosmology approximating to the truth was utterly impossible. The implacable opposition to idolatry and star-worship on the part of the Hebrew religious teachers was not without influence in clearing up the confused state of early thought. By differentiating as they did between religion and the study of the natural world, the Hebrew prophets, while more or less indifferent to the empirical study of nature, left the natural world open to investigation. Equally true is it that the rise of astrology among the Assyrians and Babylonians was a preliminary step towards the allocation of science and religion to separate spheres. It is the case, as I have elsewhere remarked, 'that the priest-astrologers of Nineveh and Babylon did not observe the stars for their own sakes, but because of their belief that the heavenly bodies controlled human destiny. Notwithstanding, this astro-theology represents a

real advance on primitive animism, with its accompanying witchcraft and sorcery. The astro-theology of Babylon was based on belief in an ordered world.'[1] The astrologers of Assyria were able to predict a solar eclipse, and those of Babylon to calculate in advance the future positions of Sun and Moon and planets with a fair degree of accuracy. The work of these Semitic star-gazers prepared the way for the cosmologies of the Greek philosophers.

It was no accident that Thales, the first Greek philosopher, was a native of Miletus, an Ionian city which had come into touch with Babylonian life and culture. Herodotus remarked that 'the pole and the sun-dial and the division of the day into twelve parts the Greeks learned from the Babylonians'.[2] That Thales was able to predict an eclipse of the Sun would indicate that he was familiar with the tables of the Babylonians. Thales was the founder of the first school of philosophy, and was himself the first of a long line of remarkable men who concerned themselves with the natural world for its own sake. Of course, neither Thales nor his successors of the Ionian school—Anaximander, Anaximenes, and Anaxagoras—nor for that matter the thinkers of the Eleatic and Pythagorean schools, made much headway in their effort to formulate a rational theory of the nature and origin of the world. The modern thinker, impressed by his own ignorance, smiles at the audacity of these men. But the significance of these philosophical cosmologists cannot be overestimated. They represented the final break with mythology and prepared the way for the scientific study of nature. 'The real advance made by the scientific men of Miletus', as a modern philosopher has put it, 'was that they left off telling tales.'[3] And what is true of the men of Miletus is true also of the pre-scientific philosophers of the Eleatic and Pythagorean schools.

[1] *The Church and Science*, pp. 15–16. [2] Book II, p. 109.
[3] Burnet, *Early Greek Philosophy*, p. 10.

To Thales the Earth was a circular disc floating on the primal substance water as a piece of wood floats on the ocean. To Anaximander the Earth was flat and placed at the centre of the world, and the Sun was a hole in the solid sky through which was visible the fire which filled the rim of the Universe. To Anaximenes the Earth—itself a condensation of dense air—was flat, and the stars were nails driven into a solid vault. Anaxagoras likewise believed that the Earth was flat, while considering that the heavenly bodies were formed of the same kind of matter. Xenophanes and Heraclitus were equally staunch in their attachment to the flat-earth theory. Parmenides, the virtual founder of the Eleatic school, however, grasped the idea of a spherical Earth, the first fruitful concept of these old cosmologists, which was taken up by the Pythagorean school. Further, two at least of this school—Philolaus and Hicetas—seem to have at least considered the possibility that this spherical Earth might not be immovable; which view, regarded as a heresy by the orthodox Pythagoreans, was later adopted by Heracleides and Aristarchus. To Plato and Aristotle and to the first astronomers the Pythagorean school passed on the doctrine, compounded of truth and error, of a spherical immovable Earth, the centre of the Universe.

This formed the starting-point of the first scientific cosmology, that of Eudoxus of Cnidus. The significance of Eudoxus lies in the fact that he was the first inductive cosmologist. He was an observer of the heavens, and to explain the phenomena which he observed he advanced his theory of concentric spheres. Whether it was ever more than a convenient working hypothesis to its author is uncertain. The late Dr. Dreyer, our leading authority on Greek cosmology, maintained that Eudoxus regarded his spheres simply as 'geometrical constructions suitable for computing the apparent paths of the planets'.[1] The system was a very com-

[1] *Planetary Systems*, p. 91

plicated one, but a brief sketch will suffice to explain its general nature. The Earth, of course, was believed to be spherical, occupying the centre of the Universe, and each celestial body was believed to be situated in the equator of a sphere revolving with uniform velocity around its poles. But Eudoxus, by observation of the heavens, was aware of the irregularities—retrogressions, variable velocities, and stationary points—of the planets, and so it was necessary to postulate the existence of other spheres. The poles of each planetary sphere were believed to be attached to larger spheres, concentric with the others, rotating round different poles with varying velocities. These poles of the second spheres were themselves rotating round other and still larger spheres. For the Sun and Moon Eudoxus found three spheres each sufficient, but in order to explain the complicated motions of the planets it was necessary to assume the existence of four spheres for each. For the fixed stars, of course, one sphere was sufficient. Finally, Eudoxus had to assume the existence of twenty-seven spheres in all. On the whole, the theory, complicated and cumbersome as it was, accounted fairly well for the observed celestial motions. It explained the motions of all the planets, except Venus and Mars, but this is not to be wondered at, considering the insufficient observational data on which Eudoxus was compelled to work. Thirty years after the theory was first propounded, it was amended by Calippus, a pupil of Eudoxus. Calippus considerably altered the system by adding a number of extra spheres to explain irregularities which had either escaped the notice of Eudoxus or which had been ignored.

In the work of Eudoxus and Calippus, as Dr. Dreyer remarks, we meet for the first time that 'mutual influence of theory and observation on each other which characterizes the development of astronomy from century to century'.

'Eudoxus', as Dreyer contended, 'is the first to go beyond mere philosophical reasoning about the construction of the Universe;

he is the first to attempt systematically to account for the planetary motions. When he has done this, the next question is how far this theory satisfies the observed phenomena, and Calippus at once supplies the observational facts required to test the theory and modifies the latter until the theoretical and observed motions agree within the limit of accuracy attainable at the time.'[1]

The Eudoxian theory was taken over by Aristotle and formed an integral part of his system of the Universe, and if it was to Eudoxus nothing more than a descriptive hypothesis, Aristotle regarded the spheres as actualities. So far as astronomy was concerned, Aristotle was not an original thinker, and his influence was, if anything, reactionary. At the same time, his acceptance of the Eudoxian cosmology stamped the foundation-stone of that edifice with the hall-mark of orthodoxy, and so the spherical shape of the Earth was not again called in question by intelligent men.

Soon after the time of Aristotle, the astronomical theory which he adopted was superseded by one more in harmony with observation. The rise of practical astronomy, by demonstrating the insufficiency of the Eudoxian hypothesis, hastened its abandonment. The necessity of regulating time and the need for an accurate calendar had stimulated observation of the Sun and Moon. So at Alexandria, under the patronage of the dynasty of the Ptolemies, a school of astronomy was founded, and systematic astronomical observations were made. The observations of the Alexandrian astronomers made possible the discoveries of Hipparchus and Ptolemy. The era of practical astronomy dawned and with the new era came a new and more elegant theory of the Universe. This was the theory of epicyclic motions, due in the first instance to Apollonius of Perge and considerably amended by Hipparchus and Ptolemy.

The epicyclic theory is not easy of explanation; but its main outline may be understood from the exposition given

[1] *Planetary Systems*, p. 107.

by the late Sir Robert Ball in his sketch of Ptolemy. Taking the typical case of Mars with its irregular motion, Ball wrote:

> 'We have the Earth at the centre and the Sun describing its circular orbit around that centre. The path of Mars is taken as exterior to that of the Sun. We are to suppose that at a point *M* there is a fictitious planet which revolves around the Earth uniformly in a circle called the deferent. This point *M* which is thus animated by a perfect movement is the centre of a circle which is carried onwards with *M* and around the circumference of which Mars revolves uniformly. It is easy to show that the combined effect of these two perfect movements is to produce exactly that displacement of Mars which observation discloses.'[1]

This is a sketch of the theory at its simplest; as astronomical observation progressed, new irregularities were discovered and had to be accounted for, and this was done by assuming the existence of additional epicycles, so that even in Ptolemy's time the theory was cumbersome to a degree. Like Hipparchus, Ptolemy regarded his theory simply as an hypothesis. Nevertheless, this was the hypothesis which he preferred. He had considered and rejected the idea, already considered by Heracleides and Aristarchus, that perhaps the Earth is actually in motion. One ground for his rejection of the idea was that a motion of translation would throw animals and movable objects right into the air. For a similar reason he turned from the idea of a rotation of the Earth on its axis—admitting, however, that such an assumption would simplify matters very much; for it would do away with the necessity of assuming a daily revolution of the star-sphere. The Ptolemaic Universe, as outlined in the *Almagest*, consisted of (1) the spherical Earth, solid and immovable at the centre; (2) the seven moving bodies, the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn, each moving in a complex system of cycles and epicycles round the Earth; and (3) the fixed stars, which were believed to be fastened to the interior of a hollow sphere.

[1] *Great Astronomers*, p. 27.

This pre-Copernican Universe was quite a homely affair. Anaxagoras, whose cosmical speculations were too daring for the good orthodox people of Athens, believed the Sun and Moon to be about the size of the Peloponnesus and therefore at terrestrial distances from the Earth. Before the scale of the Universe could even be estimated, it was necessary, however, to get a fairly accurate value of the size of the Earth. This was accomplished by Eratosthenes, who, by means of observations with the gnomon, determined the difference of latitude between Syene and Alexandria, and from this found the diameter of the Earth to be 7,850 miles and its circumference 24,662—altogether a remarkably accurate result. Posidonius at a later date secured a result less accurate though in general agreement with that of Eratosthenes. Ptolemy, on the basis of these measures of the size of the Earth, concluded that the Moon was distant 59 earth-radii and the Sun 1,210. In the case of the Moon, this value was remarkably good, but not so in the case of the Sun. Thus, at the close of the ancient period the size of the Earth and the dimensions of the Earth-Moon system had been ascertained with considerable accuracy, but the values of the solar and planetary distances were hopelessly inadequate. As to the fixed stars, the opinion prevailed that they were situated on the surface of a sphere of immense though limited extent.

The official cosmology of the Middle Ages, which received the sanction of the medieval Church, consisted not of one scheme but of three. There was first of all the so-called Mosaic world-view, based upon the first chapter of Genesis, with its firmament and waters above the firmament and its doctrine of creation in six days. This was the original cosmology of the Church Fathers. Side by side with this was the philosophic theory of Aristotle, with his doctrine of the spherical and immovable Earth, circling round which were the various celestial bodies affixed to the inside of concentric transparent spheres. This Aristotelian theory, introduced to

Europe by the Arabs, was in many respects in sharp opposition to the so-called Mosaic system, in which the Earth was regarded as flat. As Dr. Charles Singer has said, 'If the actual words of Aristotle had been confronted with the Biblical phrases, the result would have been a very serious clash.'[1] Finally, there was the Ptolemaic system, the last word of ancient science, with its theory of epicyclic motion, which differed *in toto* from the Aristotelian philosophy. But in regard to the vital question of the Earth's place in nature, there was agreement. In each of these schemes the Earth was the hub of the Universe and the end and aim of creation.

[1] *Science, Religion, and Reality*, p. 115.

I

THE HELIOCENTRIC COSMOLOGY

THE Renaissance is the watershed dividing the modern world from the medieval. About the end of the fifteenth century the human spirit, long under restraint, burst its bonds and went forth on a career of adventure and discovery. Freedom of thought and the right of free inquiry were the watchwords of the period, and its first-fruits were the Reformation, the discovery of unknown continents, and the rise of the modern sciences.

Of these sciences, the first-born was modern astronomy. The date of its nativity was the 24th of May 1543, when Copernicus received on his death-bed an advance copy of his *De Revolutionibus Orbium Coelestium*, a book dealing with the revolutions of the celestial bodies, which was indeed to revolutionize human thought. In his dedication to Pope Paul III, Copernicus stated that, finding mathematicians divided among themselves as to the true system of the world, he had resolved to seek a more satisfactory theory. He acknowledged his debt to some of the lesser Greek astronomers, who had held wildly unconventional views; he had found from Cicero, he said, that Hicetas had believed the Earth to be in motion, and that Philolaus and Heracleides had held views somewhat similar.

'Occasioned by this,' he said, 'I also began to think of a motion of the Earth, and although the idea seemed absurd, still, as others before me had been permitted to assume certain circles in order to explain the motions of the stars, I believed it would readily be permitted me to try whether, on the assumption of some motion of the Earth, better explanations of the revolutions of the heavenly bodies might not be found.'[1]

At the beginning of his first book, Copernicus showed that it is much easier to assume a rotation of the Earth in twenty-

[1] Quoted by Dreyer, *Planetary Systems*, p. 311.

four hours than to believe that all the celestial bodies are moving in the same period at an incredibly high speed; and he was at pains to refute the objection to which Ptolemy attached so much weight—that men and animals would be swept into the air by this rapid motion—for the simple reason that the air partakes also of the Earth's movement. Further, he showed that if the Earth has another motion besides that on its axis, 'it will be found, first of all in the annual circuit of the Sun, and in the stations and retrograde motions of the five planets, which are not real but only apparent phenomena caused by the Earth being in motion.'[1] 'The Sun itself occupies the centre of the Universe.'[2]

'Venus and Mercury travel round the Sun, and therefore cannot get further away from it than the convexity of their orbits allow, since the latter do not surround the Earth. The Sun, therefore, is the centre of their orbits, and the orbit of Mercury is enclosed within that of Venus, which is more than twice as great. If we take occasion of this to refer Saturn, Jupiter, and Mars to the same centre, bearing in mind the great extent of their orbits which enclose those two planets as well as the Earth, we shall not fail to find the true order of their motions. For it is certain that these are nearest to the Earth when in opposition to the Sun, the Earth being between them and the Sun, but that they are farthest from us when the Sun is between them and the Earth, which sufficiently proves that their centre rather belongs to the Sun and is the same as that round which Venus and Mercury move. It is then necessary that the space left between the orbits of Venus and Mars should be occupied by the Earth and its companion the Moon and all that is below the Moon. For we cannot in any way separate the Moon from the Earth, to which it undoubtedly is nearest, particularly as there is plenty of room for it in that space. Therefore we are not ashamed to maintain that all that is beneath the Moon, with the centre of the Earth, describe among the other planets a great orbit round the Sun, which is the centre of the world; and that what appears to be a motion of the Sun is in

[1] Dreyer, *Planetary Systems*, p. 324.
[2] Quoted, *A Source Book in Astronomy* (Shapley), p. 12.

truth a motion of the Earth; but that the size of the world is so great, that the distance of the Earth from the Sun, though appreciable in comparison to the orbits of the other planets, is as nothing when compared to the sphere of the fixed stars. And I hold it to be easier to concede this than to let the mind be distracted by an almost endless multitude of circles, which those are obliged to do who detain the Earth in the centre of the world.'[1]

Copernicus, as has been pointed out, did not produce what is now called the Copernican system.[2] He retained the idea of circular orbits, and in order to explain the outstanding irregularities in the motions of the planets he was forced to have recourse to Ptolemy's epicycles. 'Mercury', said Copernicus, 'runs in all on seven circles, Venus on five, the Earth on three, and round it the Moon on four; last Mars, Jupiter, and Saturn on five each. Thus altogether thirty-four circles suffice to explain the whole construction of the world and the whole dance of the planets.'[3]

The system of Copernicus, though he was doubtless convinced of its truth, did not appear to his contemporaries and to his immediate successors as anything more than a working hypothesis more probable than that of Ptolemy. At the same time, men were dissuaded from accepting the new system by reason of the antagonism of the ecclesiastical authorities, Romanist and Protestant alike. But within the next century, despite the opposition of theologians and philosophers, the Copernican system passed from the realm of hypotheses to that of established truth. The work of Tycho Brahe, followed by that of Kepler on the one hand and of Galileo on the other, established the new cosmology on an unassailable foundation. Tycho, who was born three years after the death of Copernicus, perceived clearly that until more accurate observations of the positions and distances of the planets had been secured, there was no hope of finding the true system

[1] Quoted by Dreyer, *Planetary Systems*, pp. 326–7.
[2] Dreyer, ib., p. 344.
[3] Quoted by Dreyer, ib., p. 343.

of the world. His first attempts at observing had demonstrated to him that the existing planetary theories—Copernican as well as Ptolemaic—agreed only very approximately with the actually observed positions of the planets, and he resolved to devote his life to practical astronomy. During many years' work at his island observatory in the Sound, the great Danish astronomer amassed an immense number of accurate determinations of planetary positions. After his exile from Denmark in 1597, Tycho made his way to Prague, where he was fortunate enough to secure the assistance of a young mathematician named Kepler. On Tycho's premature death in 1601, the priceless treasure of his accumulated observations passed into Kepler's hands.

Tycho did not accept the Copernican system. His attitude seems to have been due as much to what he took to be the teaching of Scripture [1] as to the absence of any parallactic displacement in the case of the stars; but he was even more emphatic in his rejection of the Ptolemaic theory. So he found refuge in a mediating theory which, he believed, conserved the advantages of both without the disadvantages. According to the Tychonic system, which found few adherents, the planets revolve round the Sun and are carried by the Sun round the immobile Earth, which is also the centre of the motion of the sphere of the fixed stars. So far as the planets are concerned, the Tychonic system was identical with the Copernican, and all calculations of planetary positions were the same in both systems. The Tychonic system did not retard the progress of the Copernican, but served to provide a refuge for timid astronomers in France and Italy who had found the Ptolemaic system untenable but were unable, through fear of the ecclesiastical authorities, to adopt the Copernican system. But though Tycho rejected the new cosmology, his observations on the temporary star of 1572 and on the comet of 1577 very seriously damaged the prestige

[1] Dreyer, *Tycho Brahe*, p. 177.

of the old. According to the accepted Aristotelian-Ptolemaic cosmology, there was a radical difference between the heavens and the Earth; the heavens were the region of changelessness and perfection, and the Earth of change and imperfection. That a new star could blaze out and then die away again was a definite proof that this idea of celestial changelessness was a mere figment of the imagination. Comets had, of course, been familiar for many generations, but it was generally assumed that they were atmospheric in origin and location. Aristotle had said this, and he was accepted as the final authority. Tycho at one time held this view, but he succeeded in proving by parallax measures that the comet of 1577 was farther off than the Moon.

From the raw material of Tycho's observations Kepler extracted the three laws of planetary motions in addition to the discovery which in Dreyer's opinion ought to be called his first law, that the planes of all the planetary orbits pass through the centre of the Sun.[1] The three laws which Kepler verified in the case of Mars, and surmised correctly to be true also for the other planets, are, firstly, that the planets describe not circles, as all astronomers and philosophers had hitherto believed, but ellipses, with the Sun in one of the foci; secondly, that the straight lines joining the planets to the Sun describe equal areas in equal times; and thirdly, that the squares of the times of revolution of the planets round the Sun are proportional to the cubes of their mean distances from the Sun. These laws made the Solar System intelligible and showed it to be a system not only in name but in actuality.

The work of Kepler's older contemporary Galileo was at least equally potent in undermining belief in the Ptolemaic system and in establishing the Copernican on a firm foundation. Galileo's popular fame rests, of course, on his pioneer telescopic work. He did not invent the telescope, but he was the first to turn it to the sky, and as Castelli, his friend

[1] *Planetary Systems*, p. 410.

and disciple, put it, Galileo's eye, by this means, 'may b said to have seen more than the eyes of all that had gone an to have opened the eyes of all that are to come'.[1] By mean of his little 'optic tube' he discovered that the surface of th Moon is 'full of hollows and protuberances, just like the sur face of the Earth itself',[2] and that on the bright face of the Sun which the Aristotelians declared to be without spot o blemish, black spots made their appearance from time t time. The planets appeared in his fourth telescope as littl moons, and were perceived to be worlds not dissimilar to th Earth. In the case of one of them, Jupiter, he detected th four large satellites, and at once pointed out the analog between that planet and the Earth with its one satellite; h established in the case of Venus, and strongly suspected in th case of Mars, the existence of phases similar to those of th Moon—proving, firstly, that these worlds were dark earth like bodies shining by reflected sunlight, and, secondly, tha they moved round the Sun and not round the Earth. B this time Galileo had become convinced of the truth of th Copernican system, and his telescopic discoveries deepene his conviction. In his *Dialogue on the Two Principal System of the World*, published in 1632, Galileo set forth th respective claims of the old and the new, and the effect o the book was to refute the old. In this book Galileo un doubtedly, as the ecclesiastical commission appointed t examine the book reported, 'deviated from the hypothetica standpoint by maintaining decidedly that the Earth move and that the Sun is stationary.'[3] For this, as we all know Galileo was severely punished; but his pitiful recantatio could not alter the facts of the case nor undo his work o that of Kepler. 'E pur si muove!'

By his work on dynamics Galileo did much to prepare th

[1] Fahie, *Galileo: His Life and Work*, p. 379.

[2] Quoted, *A Source Book in Astronomy* (Shapley and Howarth), p. 45.

[3] Fahie, *Galileo: His Life and Work*, p. 243.

way for Newton. Here his work was complementary to that of Kepler. The great German astronomer concerned himself with the movements of the planets in the sky; his Italian contemporary experimented with the motions of bodies on the Earth. He found by experiment—an experiment which strangely enough no one had ever made before him—that all bodies fall from the same height in equal times, and he proved the truth of this dramatically when he dropped two unequal weights from the top of the leaning tower of Pisa. He likewise discovered the relation between the space covered by a body in its descent and the time required for its descent. Newton's three laws of motion were in the main based on Galileo's pioneer work on falling bodies. These laws are, firstly, that every body continues in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by force applied to it from without; secondly, that change of motion is proportional to the applied force and takes place in the direction in which the force acts; and thirdly, that to every action there is always an equal and opposite reaction.

Newton, who was born in the year of Galileo's death, was destined to place the coping-stone on the edifice of the new cosmology; or rather, we may say, he supplied the foundation. His work on the laws of motion led him after many years' work to the formulation of what is called the law of gravitation. 'Every particle of matter in the Universe attracts every other particle with a force varying directly as the product of their masses and inversely as the square of the distance between them.' By his theory of gravitation, Newton gave the explanation of the laws of falling bodies discovered by Galileo and the laws of planetary motion formulated by Kepler. Under the sweep of his law Newton effected a synthesis of the observed facts of astronomy and dynamics, so that a large number of apparently disconnected facts were shown to be the outcome of universal law. The

fall of the apple to the ground was proved to be due to th same cause as the motion of the Moon round the Earth 'The law of the heavens was now the law of the Earth.' During the century which followed the publication of th *Principia* in 1687, the chief aim of astronomers was to shov that from the Newtonian law it was possible to deduce fron the positions and motions of the eighteen known bodies ir the Solar System—Sun, planets, and satellites—at any giver time, their positions and motions at some later period and t prove that these were in agreement with actual observation This tremendous task—the astronomical task of the eigh teenth century—was carried through by the school of brillian French mathematicians, chief among them Lagrange anc Laplace, aided by the painstaking English observers who laic the foundations of what is called fundamental astronomy.

The scale of this vast system was fixed with a certair approach to accuracy when Cassini, from measures of th parallax of Mars, obtained in 1672 a value for the Sun's distance from the Earth of eighty-seven million miles, whicl is six million miles or about 6½ per cent. short of the truth This unit distance being known, all other distances in th Solar System could be deduced from Kepler's laws. Th diameter of the Solar System before the discovery of Uranus was believed to be of the order of 1,560 million miles.[2] Bu it was, after all, only an obscure corner of the Univers which claimed the attention of the great astronomers fron Copernicus to Laplace. These great men had laid th foundation of our knowledge of the Solar System—it structure, and the motions and physical aspect of the bodie composing it. Their cosmology was heliocentric, even as tha of the ancients was geocentric. Regarding the great univers

[1] Singer, *Science, Religion, and Reality*, p. 146.

[2] Ferguson in 1756 gave the distance of Saturn from the Sun a 780 million miles. *Astronomy Explained upon Sir Isaac Newton's Prin ciples*, i, p. 37 (ed. of 1811).

outside, they entertained only the haziest notions. When men like Kepler came to discuss the nature of the stars, they were as much in the dark as was Ptolemy in respect of the planets.

Kepler's laws gave no clue to the distances of the innumerable stars which the telescopes of the seventeenth and eighteenth centuries had shown to be scattered with such rich profusion; and the stars obstinately refused to yield up, even to the ablest telescopic observers of these centuries, the secret of their distance. It had long been known that no terrestrial base-line was nearly long enough to permit astronomers to measure stellar parallaxes as they had measured the parallaxes of Sun and planets; and that it was necessary to make use of a vastly longer base-line, the diameter of the terrestrial orbit, by means of which an annual parallax might be measured. One of the weightiest objections to the Copernican system was that if the Earth were really in motion, such an annual parallax should be a measurable quantity, and yet it could not be measured. Granting the terrestrial motion, the absence of an appreciable parallax indicated a distance for the sphere of the fixed stars much greater than the medieval mind was willing to concede. This did not weigh with Copernicus, for he was prepared to argue that a very great distance intervened between the orbit of Saturn and the star-sphere, which he believed to be immovable.[1] Galileo was willing to admit the existence of a 'vast vacancy' between Saturn and the stars.[2] Tycho Brahe was more cautious. He placed Saturn at a distance of nearly fifty million miles and the star-sphere at a little under sixty millions. Kepler was prepared to admit a much greater distance than this. He computed the distance of the stars at 420 thousand million miles. At one stage he came near to accept the bold thought of Bruno that the stars were akin to

[1] Dreyer, *Planetary Systems*, p. 328.
[2] Fahie, *Galileo: His Life and Work*, p. 256.

the Sun, but apparently he was unable to emancipate himself from the medieval view that the fixed stars were really fixed to a solid sphere, 'two German miles in thickness' centred in the Sun. To Kepler the Sun was the centre of the Universe.[1]

By the close of the seventeenth century the solid star-sphere which Kepler had inherited from the ancient cosmologists had been finally relegated to the limbo of discarded hypotheses. Thus, in his *Cosmotheoros*, published in 1698, three years after his death, Huyghens, the great Dutch astronomer and mathematician, set forth the theory that the stars are suns distributed uniformly throughout space out to an infinite distance, and that each star is the centre of a planetary system. The conviction had now begun to force itself on astronomers that the stars must be at still greater distances than Kepler had been willing to concede. Huyghens deduced a distance for Sirius of about 20,000 times the distance of the Sun—of the order of a billion miles,[2] and Newton estimated that a star of the first magnitude should show an annual parallax of 0·2″,[3] corresponding to between 9 and 10 billion miles. But these were simply more or less plausible estimates. The farthest known distance in the eighteenth century was that of Saturn, computed, from Cassini's value of the solar parallax, at 780 million miles.

[1] Dreyer, *Planetary Systems*, p. 411.
[2] Gore, *The Visible Universe*, p. 183.
[3] Dyson, Supplement to *Nature*, 21 March 1927, p. 33. See also Newton's discussion of the question of star-distance in *A Source Book in Astronomy* (Shapley and Howarth), pp. 86–8.

II

HERSCHEL'S COSMOLOGY

ON March 1st 1774 a German musician, resident in the old English town of Bath, turned to the stars a reflecting telescope made with his own hands, with which he viewed Saturn's ring and 'the lucid spot in Orion's sword belt'.[1] Thus commenced the observing career of one who is entitled with some justice to be called the Copernicus of the Stellar System.

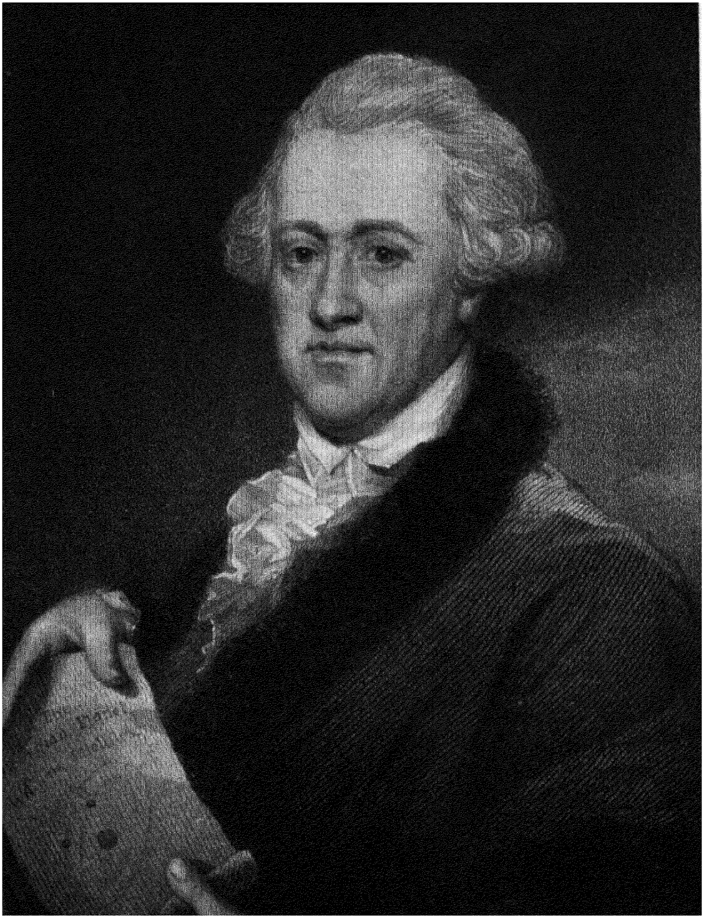
Prior to the time of William Herschel, stellar astronomy had made surprisingly little progress. The attention of astronomers had been of necessity concentrated on the problem of the structure of the Solar System, and the stars had been observed more particularly as convenient reference-points by which the positions of Moon and planets could be fixed with some degree of accuracy and their paths mapped out in the sky. A few isolated discoveries had indeed been made. Galileo had discovered the milky light of the Galaxy to be due to the combined shining of innumerable faint stars. Temporary stars were observed by Tycho, Galileo, and Kepler, and one or two of the more prominent variable stars had been detected by Fabricius, a Dutch amateur, and by Montanari, an Italian observer. A few double stars had been discovered—almost accidentally, because they could not escape discovery—by Riccioli in Italy, Huyghens in Holland, and Hooke in England. The Orion nebula had 'swam into the ken' of Huyghens in 1656, and the cluster in Hercules into that of Halley in 1714. Finally, in 1718, Halley obtained definite proof of the proper motions of the four bright stars, Sirius, Arcturus, Betelgeux, and Aldebaran, thus verifying a brilliant guess on the part of that versatile genius, Giordano Bruno; and by 1756 the proper motions of fifty-seven stars had been catalogued by Tobias Mayer of Göttingen.

[1] *Collected Scientific Papers*, i, p. xxv.

So much for observation, which lagged behind speculation. Bruno had assigned to the stars the role of suns analogous to ours, a view which even Kepler was not prepared to accept. Huyghens, as already mentioned, had concluded that the stars, so far from being affixed to the inner surface of a sphere, were scattered uniformly throughout a space of infinite extent, and that each star was the centre of a planetary system. The great Dutchman, however, expressed no view on the nature and significance of the Milky Way. This was first done by an English amateur, Thomas Wright, of Durham, who outlined the theory that the Milky Way was an optical effect due to the great extension of the Stellar System in one plane. This view was adopted by the great philosopher Kant in his cosmological speculation, and by Lambert, a German thinker of rare penetration, who wrote of the Milky Way as the 'ecliptic of the fixed stars'. Wright, Kant, and Lambert seem, indeed, to have anticipated the disc-theory of Herschel. But their disc-theories were of the nature of pure speculation, unsupported by observational evidence. The field of stellar astronomy was, then, virtually untrodden when Herschel commenced his surveys of the heavens, in the course of one of which he incidentally discovered the planet Uranus and thus doubled the diameter of the Solar System. Right from the beginning of his career, he kept before him the aim of arriving at a tenable cosmology. 'A knowledge of the construction of the heavens', he wrote in 1811, 'has always been the ultimate object of my observations.' [1]

Just as the cosmology of Copernicus made as a fundamental assumption the motion of the Earth, so right at the bottom of the cosmology of Herschel is that of the motion of the Sun, carrying with it the Earth and the other planets, relative to the stars. In the light of the measured proper motions of the brighter stars, Herschel asked in his paper of 1783, 'does it not seem natural that . . . most probably every

[1] *Collected Scientific Papers*, ii, p. 459.



WILLIAM HERSCHEL

star in the heavens is more or less in motion ? . . . If the proper motion of the stars in general be once admitted, who can refuse to allow that our Sun, with all its planets and comets, that is, the Solar System, is no less liable to such a general agitation as we find to obtain among all the rest of the celestial bodies ?'[1] The problem was to detect this motion in an apparent drift of the stars in the opposite direction, just as the Earth's motion may be found in the retrogressions of the planets. If the Sun is moving in a certain direction, as Herschel clearly perceived, the stars in front of the Sun will appear to spread out and those behind to draw together. If the stars were at rest, the problem would be a comparatively simple one; but it is rendered much more complex by the fact that each individual star has its own proper motion, and presumably these proper motions are at random. The apparent proper motions of the stars must therefore be decomposed into two parts, the real motions of the stars and the apparent motion resulting from the translation of the Solar System. 'We ought, therefore,' said Herschel, 'to resolve that which is common to all the stars which are found to have what is called a proper motion into a single real motion of the Solar System, as far as that will answer the known facts, and only to attribute to the proper motion of each particular star the deviations from the general law the stars seem to follow in those movements.'[2] Herschel treated the problem in a very simple manner. Taking the proper motions of seven bright stars—Sirius, Arcturus, Altair, Regulus, Procyon, Castor, and Pollux—he separated what he took to be their real motions from their common motion due to the drift of the Sun and found the Sun to be moving towards a point in the constellation Hercules, the 'apex' of the Sun's way being marked by the star Lambda Herculis. As to the rate of motion, Herschel concluded that 'we may in a general way estimate that the solar motion can certainly

[1] *Collected Scientific Papers*, i, p. 115. [2] Ib. i, p. 120.

not be less than that which the Earth has in her annual orbit'.[1]

At the outset of his quest after the structure of the heavens, Herschel realized that the first desideratum was the accumulation of data on which a rational theory could be based. In dealing with the problem, there are three possible lines of attack, by means of the distances, the motions, and the distribution of the stars. It is evident that if all stellar distances were measured, the shape and size of the Stellar System would be easily determined, and that if in addition the direction and rate of motion of every star was known, the structure of the system could be ascertained. But in Herschel's time no stellar distances were known. Herschel made several fruitless efforts to measure stellar parallaxes, but his large reflectors were ill-adapted for making delicate determinations of this kind. Nor was the second mode of approach much more hopeful. Comparatively few proper motions were known with any approach to accuracy. Herschel found both of these avenues closed to him. He was therefore compelled to concentrate on the apparent distribution of the stars, and to seek by an extensive series of observations to outline the shape of the Stellar System and to arrive at an approximate idea of its extent.

In his first paper on 'The Construction of the Heavens', dated April 1784, Herschel described the Milky Way as 'nothing but a stratum of fixed stars',[2] and showed clearly that despite its ring-shaped appearance it could not possibly be a ring. 'Should we imagine it to be an irregular ring of stars in the centre nearly of which we must then suppose the Sun to be placed, it will appear not a little extraordinary that the Sun, being a fixed star like those which compose this imagined ring, should just be in the centre of such a multitude of celestial bodies, without any apparent reason for this singular distinction.'[3] There is no evidence that Herschel was at this

[1] *Collected Scientific Papers*, i, p. 125. [2] Ib. i, p. 160. [3] Ib. i, p. 161.

stage acquainted with the speculations of Wright, Kant, and Lambert; but at all events, having rejected the ring theory as an explanation of the Milky Way, he reached an explanation very similar to theirs.

'Suppose a number of stars arranged between two parallel planes, indefinitely extended every way but at a given considerable distance from each other; and calling this a sidereal stratum, an eye placed somewhere within it will see all the stars in the direction of the planes of the stratum projected into a great circle, which will appear lucid on account of the accumulation of the stars; while the rest of the heavens at the sides will only seem to be scattered over with constellations, more or less crowded according to the distance of the planes or number of stars contained in the thickness or sides of the stratum. . . . . On our supposition, every star in this stratum not very near the termination of its length or height will be so placed as also to have its own galaxy, with only such variations in the form and lustre of it as may arise from the particular situation of each star.'[1]

When he came to actual observation, he found support for this provisional hypothesis. He noted the 'remarkable purity or clearness in the heavens' towards Leo, Virgo, and Coma Berenices on the one hand and towards Cetus on the other, that is towards the regions of the heavens more distant from the Galaxy, whereas he observed the 'ground of the heavens' to be what he called 'troubled' the nearer he approached the galactic zone. 'It was a good while', he wrote, 'before I could trace the cause of these phenomena; but since I have been acquainted with the shape of our system, it is plain that these troubled appearances when we approach the sides are easily to be explained by ascribing them to some of the distant straggling stars that yield hardly light enough to be distinguished. And I have indeed often experienced this to be actually the cause by examining these troubled spots for a long while together, when at last I generally perceived the

[1] *Collected Scientific Papers*, i, pp. 160–2.

stars which occasioned them. But when we look towards the poles of our system where the visual ray does not graze along the side, the straggling stars of course will be very few in number; and therefore the ground of the heavens will assume that purity which I have always observed in those regions.'[1]

Assuming this to be the true explanation of the Galaxy, the problem before Herschel was to 'find the Sun's place in the sidereal stratum' and to get at least a rough outline of the stratum and an estimate of the scale on which it was constructed. He attacked this problem by the method of star-gauging, 'which consists in repeatedly taking the number of stars in ten fields of view of my reflector very near each other and by adding their sums and cutting off one decimal on the right, a mean of the contents of the heavens in all parts which are thus gauged is obtained.'[2] Even at this early stage of his investigations it was evident to Herschel that the star-density increased rapidly near the edges of the Milky Way. In his second paper he stated that in the most crowded parts of the Galaxy as many as 588 stars were to be counted in one field of view fifteen minutes of arc in diameter,[3] while in other parts of the sky he came upon fields which were practically empty.

In his paper of 1785 Herschel, making use of a large number of gauges, was able to give an outline of the Stellar System and a rough estimate of its extent. The resultant theory of the Stellar System was based on two assumptions, that his gauging telescope was capable of penetrating to the frontiers of the system, and that the stars composing the system were scattered with some approach to uniformity. As a result of a large number of star-gauges, Herschel was able to write thus:

'That the Milky Way is a most extensive stratum of stars of various sizes admits no longer of the least doubt, and that our Sun is actually one of the heavenly bodies belonging to it is evident. I have now viewed and gauged this shining zone in

[1] *Collected Scientific Papers*, i, pp. 253–4. [2] Ib. i, p. 162. [3] Ib. i, p. 246.

almost every direction, and find it composed of stars whose number by the account of these gauges constantly increases and decreases in proportion of its apparent brightness to the naked eye.'[1]

In formulating a plausible theory of the shape and extent of the Universe, Herschel had to take account of the great cleft or 'bifurcation' in the Milky Way from Cygnus southwards; accordingly he assumed a division of the stratum into two branches, and he sketched the Stellar System as a thin cloven disc of irregular outline.

Taking the number of stars recorded by each gauge as indicative of the depth of the stratum at that particular part of the sky, Herschel was able to throw out his sounding-line, as it were, to the confines of the stratum and thus to fix the position of the Sun. This he found to be not quite central, the Sun being a little closer to the north galactic pole than to the south, and slightly farther from the limits of the system in the direction of Aquila than in that of Canis Minor. 'In the sides of the stratum opposite to our situation in it'—namely, towards the galactic poles—the system 'cannot extend to 100 times the distance of Sirius'; while along the plane he could penetrate to a distance of 497 times the distance of Sirius.[2] No reliable measures of stellar parallax had been made in Herschel's time and no stellar distance was known with certainty. But if we take the modern value of the distance of Sirius, we may compute that according to Herschel's disc-theory the Stellar System, strictly finite in extent, had a thickness of 1,200 light-years and a diameter of 6,800.[3]

[1] *Collected Scientific Papers*, i, p. 223. [2] Ib. i, p. 247–8.

[3] Cf. Gore, *The Visible Universe*, p. 231. Dr. See (Paper on 'Determination of Depth of the Milky Way', reprinted in W. L. Webb's *Brief Biography of T. J. J. See*, p. 207), taking the average distance of the first-magnitude stars at 135 light-years, deduced for Herschel's disc a thickness of 21,600 light-years and a depth of 1,237,680 light-years. But when Herschel took the distance of Sirius as his unit it was not as the distance of an average first-magnitude star but as the distance of what was presumably the nearest star. Light, said Herschel (*Collected Scientific Papers*, ii, p. 215), must take at least 6 years and 4½ months to

But to Herschel this vast system by no means exhausted the Universe. Herschel's favourite name for the stratum was 'our nebula', and this in itself was suggestive. He had been remarkably successful in resolving into individual stars many of the misty spots listed by the French astronomer Messier in his catalogue of nebulae, and to these and to many others, which he discovered by means of his own telescopes, he assigned the rank of 'Milky Ways' or sidereal systems, independent of 'our nebula' and of each other. This was not of the nature of mere speculation; it was a deduction from the star-gauges.

'It is true that it would not be consistent confidently to affirm that we were on an island unless we had everywhere found ourselves bounded by the ocean, and therefore I shall go no further than the gauges will authorize; but considering the little depth of the stratum in all these places which have been actually gauged, to which must be added all the intermediate parts that have been viewed and found to be much like the rest, there is but little room to expect a connexion between our nebula and any of the neighbouring ones.' [1]

Herschel divided his 'nebulae', of which he enumerated at least 1,500, into four classes or 'forms' according to the degree of their condensation. 'We inhabit', he said, 'the planet of a star belonging to a compound nebula of the third form' [2]—'a very extensive branching compound congeries of many millions of stars'.[3] From this 'retired station', as he pic-

travel from Sirius to the observer. According to modern determinations, Sirius is 8·6 light-years distant; so that Herschel's estimate was not very wide of the mark.

[1] *Collected Scientific Papers*, i, p. 247.

[2] Ib., p. 245. Herschel took over from Huyghens and the less prominent thinkers who followed him the view that the stars were the centres of planetary systems. 'Every star', he said in 1789, 'is probably of as much consequence to a system of planets, satellites, and comets as our own Sun' (*Collected Scientific Papers*, i, p. 330); and in keeping with the prevalent view of the eighteenth century, he viewed every hypothetical planet as the abode of life. But in 1802, after his discovery of binary stars, he concluded that 'we can only look for solar systems among the insulated stars' (*Collected Scientific Papers*, ii, p. 201).

[3] Ib. i, p. 252.

turesquely put it, he sought to get an idea of the sizes and distances of these other island universes. Some of them he concluded to be much larger than our own system.[1] He computed the distance of 'a nebula whose light is perfectly milky' at 'six or eight thousand times the distance of Sirius'.[2] Again, taking the distance of Sirius at eight light-years, this would give 48,000 or 64,000 light-years. Later he dealt with still more distant objects, and estimated the distance of the fainter nebulae visible in his great telescopes as two million light-years.[3]

Herschel believed that the various 'nebulae', or separate galaxies, had been formed as the result of the break-up of a greater stellar stratum. 'A few stars, though not superior in size to the rest, may chance to be rather nearer each other than the surrounding ones; for here also will be formed a prevailing attraction in the combined centre of gravity of them all, which will occasion the neighbouring stars to draw together.'[4] Thus will be formed systems in various degrees of condensation, from loose irregular clusters to highly condensed. 'When a nebulous stratum consists chiefly of nebulae of the first and second form, it probably owes its origin to what may be called the decay of a great compound nebula of the third form; and the subdivisions which happened to it in length of time, occasioned all the small nebulae which sprung from it to lie in a certain range according as they were detached from the primary one. In like manner our system, after numbers of ages, may very possibly become divided so as to give rise to a stratum of two or three hundred nebulae; for it would not be difficult to point out so many beginning

[1] *Collected Scientific Papers*, i. 254. Cf. his remarks to Miss Burney, quoted by Clerke, *The Herschels and Modern Astronomy*, p. 67.

[2] Ib. i, p. 255.

[3] Ib. ii, p. 215. In 1811 he told the poet Campbell that he had observed stars two million light-years away; so evidently he did not revise this estimate.

[4] Ib. i, p. 224.

or gathering clusters in it.'[1] Down to the close of his career Herschel maintained that smaller systems were formed in this way out of larger. The observations detailed in his paper of 1814 'authorize us to anticipate the breaking-up of the Milky Way in all its minute parts as the unavoidable consequence of the clustering power arising out of these preponderating attractions which have been shown to be everywhere existing in its compass'. The stars of the Milky Way, he believed, were being 'irresistably drawn into groups', a process which will go on 'till they come up to what may be called the ripening of the globular form and total insulation, from which it is evident that the Milky Way must be finally broken up and cease to be a stratum of scattered stars'.[2]

For many years it was assumed that the disc-theory, as set forth in 1785, represented the Herschelian cosmology in its final stage. Arago, the brilliant French astronomer, whose popular works had so great a vogue in their day, expounded the disc-theory in this way, and he was followed by a host of other writers, both professional astronomers and popularizers. Proctor pointed out in 1872 that these writers proceeded on the assumption that 'extracts might be made from any part of any paper, without reference to the position which that paper chanced to occupy in the complete series', and he went on to say that 'it does not seem to have been noticed that not only was there a progression in the ideas as well as the work of the great astronomer, but that there was a complete change of his opinions during the progress of his labours'.[3] Proctor, after a careful study of Herschel's later papers, was led to the view, at which the German astronomer Struve arrived independently at an earlier date, that Herschel abandoned the disc-theory in the latter part of his career. It would be more correct to say that he modified it somewhat.

He was led to modify his earlier views by his work along

[1] *Collected Scientific Papers*, i, p. 252–3. [2] Ib. ii, p. 540.
[3] *The Universe of Stars*, p. 183.

two different lines of study. In the first paper he had assumed that the stars were scattered throughout the system with some approach to uniformity; but it should be noticed that the assumption was regarded as only approximately true. In the paper of 1785 he admitted that 'in all probability there may not be two or three of them in the heavens whose mutual distance may be equal to that of any other two given stars'; but he concluded 'that when we take the stars collectively there will be a mean distance which may be assumed as the general one'.[1] But he distinctly defined the Stellar System as a 'compound nebula', and in the same paper he remarked that it would not be difficult to point out two or three hundred 'gathering clusters' in the Stellar System.[2] Indeed, when Herschel came to deal almost incidentally with the question of origins he remarked that our nebula 'most probably owes its origin to many remarkably large as well as pretty closely scattered small stars that may have drawn together the rest'.[3] Still, at this stage he would seem to have thought that these various systems, as it were, cancelled each other out, and that on the average a uniform distribution might be postulated.

In the paper of 1802 Herschel stated quite frankly that he had modified his views, although he nowhere stated that he had renounced the disc-theory. In the seventeen years between 1785 and 1802, however, he had been led, as the result of much more extensive observations, to realize that 'our nebula' was more 'compound' than he had imagined. 'Though the Sun and all the stars we see may truly be said to be in the plane of the Milky Way, yet I am now convinced by a long inspection and continued examination of it that the Milky Way consists of stars very differently scattered than those immediately about us.'[4] In 1806 he suggested that the Sun and the nearer stars might form 'a very extensive

[1] *Collected Scientific Papers*, i, p. 246. [2] Ib., p. 253. [3] Ib., p. 252.

[4] Ib. ii, p. 200. Herschel undoubtedly modified this hasty conclusion later. Cf. p. 591.

system',[1] presumably a sub-system; while in 1802, discussing the collections of small stars that are profusely scattered over the Milky Way, he wrote: 'On a very slight examination it will appear that this immense stellar aggregation is by no means uniform. The stars of which it is composed are very unequally scattered and show evident marks of clustering together into many separate allotments';[2] and he instanced as an example the space between Beta and Gamma Cygni, where he thought the stars were 'clustering towards two different regions'. He specially emphasized the 'milky appearances' in the Milky Way which he called clustering collections, which he found to be brighter about the centre and fainter near their borders, and which were obviously separate groups.

By this time, too, Herschel's confidence in the stellar nature of all the nebulae, and consequently in the universal validity of the island universe theory, was beginning to be shaken. In his paper of 1791 on 'nebulous stars properly so-called', Herschel drew attention to a 'cloudy star' of this kind in the nineteenth cluster of his sixth class. 'Cast your eye on this cloudy star. . . . Our judgement, I may venture to say, will be that the nebulosity about the star is not of a starry nature.'[3] He gave a list of other instances; and was driven to invoke as explanation the existence of 'a shining fluid of a nature totally unknown to us'.[4] Even in this preliminary paper, he showed that the so-called planetary nebulae and the diffused nebulae of which the Great Nebula in Orion is typical were more likely to be composed of shining fluid than of separate stars.[5] This newer view of certain of the nebulae led naturally to a revised estimate of their distances. We say 'certain of the nebulae' advisedly. Herschel at this stage was by no means prepared to assume that all nebulae were composed of shining fluid. He carefully guarded himself against any

[1] *Collected Scientific Papers*, ii, p. 359. [2] Ib. ii, p. 211. [3] Ib. i, p. 416.
[4] Ib. i, p. 422. [5] Ib. i, pp. 423–4.

such construction of his views. He merely said that 'perhaps it has been too hastily assumed that all milky nebulosity, of which there is so much in the heavens, is owing to starlight only'.[1] In 1802 he differentiated sharply between 'nebulae' and 'milky nebulosity', which latter phenomenon he took to be of 'two different kinds', unresolved star-groups and the stuff which he had provisionally called 'shining fluid'.[2] The island universe theory, then, had not been abandoned; its author had simply been led to question and then to reject its universal validity.

Struve and Proctor laid great stress on Herschel's paper of 1811 as confirmatory of their contention that he had abandoned the disc-theory. But they do not appear to have observed that Herschel nowhere avowed the renunciation of the theory, which he would surely have done had he actually abandoned it in its entirety. Even in this paper, Herschel was at great pains to indicate just where and why his views had changed.

> 'If,' he wrote, 'it should be remarked that in this new arrangement I am not entirely consistent with what I have already in former papers said on the nature of some objects that have come under my observation, I must freely confess that by continuing my sweeps of the heavens my opinion of the arrangement of the stars and their magnitudes and of some other particulars has undergone a gradual change; and indeed, when the novelty of the subject is considered, we cannot be surprised that many things formerly taken for granted should on examination prove to be different from what they were generally but incautiously supposed to be.'

And he went on, in the same cautious vein, to say that

> 'for instance, an equal scattering of stars may be admitted in certain calculations; but when we examine the Milky Way or the closely compressed clusters of stars of which my telescopes have recorded so many instances, this supposed equality of scattering must be given up. We may also have surmised nebulae to be no other than clusters of stars disguised by their very great distance,

[1] *Collected Scientific Papers*, i, p. 423. [2] Ib. ii, p. 213.

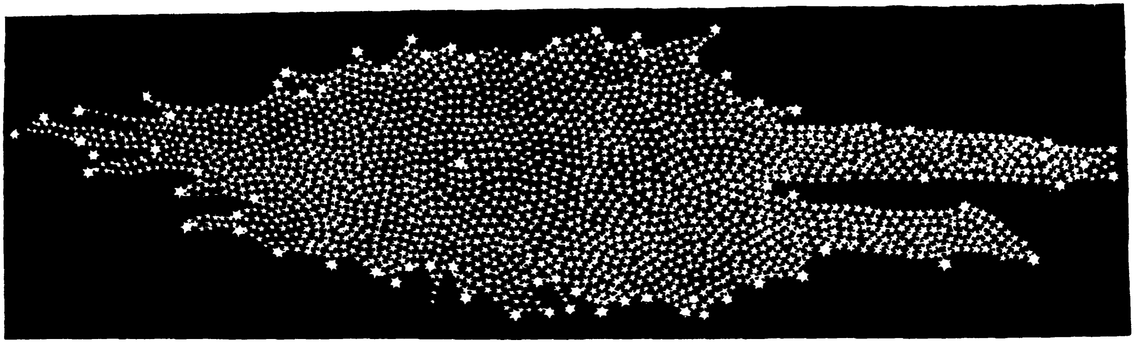
but a longer and better acquaintance with the nature of nebulae will not allow a general admission of such a principle, although undoubtedly a cluster of stars may assume a nebulous appearance when it is too remote for us to discern the stars of which it is composed'.[1]

From this somewhat lengthy and involved quotation it is evident that Herschel neither abandoned the disc-theory nor the view that numbers of nebulae were external universes.

The paper of 1811 dealt with cosmogony rather than cosmology, and the nebulae with which Herschel was concerned were chiefly those which he believed to be links in his hypothetical chain of development from 'shining fluid' to stars. In the paper of 1814 he considered both nebulae and star-clusters, and emphasized the importance of a class which he called 'objects of an ambiguous construction',[2] a class consisting of genuine masses of nebulosity and of irresolvable star-clusters sunk at vast distances in space. At the close of the paper he briefly discussed the Milky Way and remarked that 'if ever it consisted of equally scattered stars, it does so no longer; for by looking at it in a fine night we may see its course between the constellations of Sagittarius and Perseus affected by not less than eighteen different shades of glimmering light, resembling the telescopic appearances of larger, easily resolvable nebulae'.[3] He was coming to view the Milky Way as a stratum of clusters rather than of evenly scattered stars; he deliberately used the word stratum to describe it. Arguing from the influence of what he called the 'clustering power', he reasoned that the Milky Way would be finally broken up and cease to be a stratum of scattered stars, from which he was led to conclude that as the Milky Way could not last for ever, its past duration could not be called infinite.[4]

In this paper Herschel, then in his seventy-sixth year,

[1] *Collected Scientific Papers*, ii, p. 459. [2] Ib. ii, p. 526. [3] Ib. ii, p. 540. [4] Ib. ii, pp. 540–1.



The Stellar System according to Herschel's Disc-theory

stated that he was engaged in an attempt to fathom the extent of the Universe; and in his final papers, in 1817 and 1818, he dealt with this question. From these papers we are able to deduce the final form of his cosmology. He dealt with the extent of the Stellar System and the relative distance of star-clusters; and in grappling with these problems he devised and applied a second method of star-gauging which several popular writers have confused with the first. The two methods, however, were quite distinct, and ought to be carefully distinguished from each other. In the first, one telescope was used on different regions of the sky; in the second, the same regions were examined with different instruments. This second method suffered undue disparagement at the hands of Proctor, who wrote of it in 1872: 'I conceive that no question can exist that the principle is unsound and that Herschel would himself have abandoned it had he tested it earlier in his observing career, and when not his mental power but his mental elasticity was greater than at the advanced age which he had now reached.'[1] As a matter of fact, neither Proctor nor Gore, who followed him in his study of Herschel's papers, seem to have fully understood the new method.

Herschel assumed 'a certain properly modified equality of scattering' in the case of the stars taken as a whole, and this despite his reasoned conclusion that the Stellar System was largely an assemblage of clusters. He did not go back to the idea that individual stars were on the average distributed with an approach to uniformity; 'the equality I shall here propose does not require that the stars should be at equal distances from each other, nor is it necessary that all those of the same nominal magnitude should be equally distant from us'. His principle was that on the average and as a class stars of one magnitude are nearer to us than stars of a fainter magnitude. 'Since it is evident that we cannot mean to affirm that the stars of the fifth, sixth, and seventh magnitudes

[1] *The Universe of Stars*, p. 192.

are really smaller than those of the first, second, and third, we must ascribe the cause of the difference in the apparent magnitudes of the stars to a difference in their relative distances from us.'[1] This is a principle which nearly a century later was used with valuable results by Kapteyn in his work on stellar distances and distribution. Finally, Herschel assumed a certain mean size for all the stars,[2] an assumption not altogether discredited at the present time; therefore the fainter the star, the greater the distance.[3]

In his discussion of the construction and extent of the Milky Way, Herschel selected a number of the brighter patches and applied to them his second method of star-gauging. The greater the aperture of the telescope, the more stars he saw in these regions. In his criticism of the second method of star-gauging, Proctor said that such regions as that in Perseus 'if the principle were true, must be long spike-shaped star-groups whose length is directed exactly towards the astronomer on Earth—an utterly incredible arrangement even if we could believe in the dynamical possibility of such grouping'.[4] The double cluster in Perseus 'if rightly interpreted by Herschel in 1818 forms a long, thin, almost cylindrical array of stars happening by a singular chance to have its length directed exactly towards our Earth! As there are two clusters indeed there are two such enormously long and slender arrays thus strangely adjusted'.[5] Certainly Herschel's own words lent themselves to such an interpretation; but he does not seem to have been at all committed to the view that in the case of such regions of the Milky Way, his telescope was really penetrating farther and farther into space; he had always recognized the existence of clustering regions.

'With regard to these gauges which on a supposition of an equality of scattering were looked upon as gauges of distance, I have now to remark that although a greater number of stars

[1] *Collected Scientific Papers*, ii, p. 576. [2] Ib., p. 579. [3] Ib., p. 585.
[4] *The Universe of Stars*, p. 192. [5] *Our Place Among Infinities*, p. 284.

in the field of view is generally an indication of their greater distances from us, these gauges, in fact, relate more immediately to the scattering of the stars of which they gave us a valuable information such as will prove the different richness of the various regions of the heavens'.[1]

Applying his principle, however, to the ordinary galactic star-fields, Herschel concluded that 'the utmost stretch of the space-penetrating power of the 20-feet telescope could not fathom the profundity of the Milky Way', and that 'the stars which were beyond its reach must have been farther from us than the 900th order of distance'.[2] In his paper of 1818—his last paper on the construction of the heavens—he maintained that his gauges 'leave no doubt of the progressive extent of the starry regions. We may conclude that when our gauges will no longer resolve the Milky Way into stars, it is not because its nature is ambiguous, but because it is fathomless.'[3] The mistranslation of the last word by Struve led to the theory that the Stellar System was infinite in extent. This, however, was not in Herschel's mind; he only meant that with the telescopic power at his command he could not fathom the profundity of the Milky Way. He still viewed the Stellar System as a disc or stratum composed of innumerable local clusters, and immensely more extended in the galactic plane than he believed to be possible in 1785. He emphasized the existence of regions of exceptional richness in the galactic plane, but the Milky Way remained for him in the main an optical effect. 'Not only our Sun but all the stars we can see with the eye are deeply immersed in the Milky Way and form a component part of it.'[4]

In his final paper Herschel concerned himself with the distances of globular and other clusters. Assuming that the component stars of such clusters are, generally speaking,

[1] *Collected Scientific Papers*, ii. p. 588. Proctor did not grasp the significance of these words, but Gore in his latest discussion of the subject laid emphasis on them (*Astronomical Essays*, p. 196).

[2] Ib. ii, pp. 588–9. [3] Ib. ii, p. 609. [4] Ib. ii, p. 591.

comparable with Sirius in size, he laid down the principle that the relative distances of these clusters can be determined by the telescopic powers necessary to reveal and resolve them. This principle, though dismissed by Proctor as untenable, has been rehabilitated in recent years by the work of Shapley. The final conclusion to which Herschel was led was that many of his ambiguous objects were clusters of stars sunk at immense distances in outer space, while the distances of true nebulae may probably not exceed the 900th order,[1] which, in his paper of 1817, he suggested as a possible distance for the frontiers of the Stellar System.[2] Herschel held it to be highly probable that 'some of the cometic, many of the planetary, and a considerable number of the stellar nebulae are clusters of stars in disguise on account of their being so deeply immersed in space that none of the gauging power of our telescopes have hitherto been able to reach them'.[3]

The cosmology of 1818 was much more complex than that of 1785. Herschel had indeed abandoned the theory of an equal scattering on the average of 'insulated' stars, and had recognized that the vast Stellar System was rather a cluster of clusters than a homogeneous whole. But at the close of his career he viewed the galactic zone as in the main an optical effect and the Stellar System as a disc, vastly more extended than that of 1785. And while a large proportion of the nebulae were now regarded by him as masses of primeval chaos out of which the suns and worlds of the future would be formed, while he had formulated a cosmogony incidentally in his search after a cosmology, it is not strictly true to say, as an acute biographer said, that his 1,500 universes 'logically ceased to exist'[4] after 1802. Many, perhaps most of them, had; but there can be no doubt that Herschel in 1818 regarded at least a number of these dim misty objects as island universes, co-equal with the Stellar System.

[1] *Collected Scientific Papers*, ii. p. 611. [2] Ib. ii, p. 591. [3] Ib. ii, p. 611.
[4] Clerke, *The Herschels and Modern Astronomy*, p. 72.

III

NINETEENTH-CENTURY COSMOLOGICAL THOUGHT

In one of his numerous discussions of Herschel's researches into the construction of the heavens, Proctor remarked that

'had the notice of astronomers been attracted by Herschel's work in its initial stages, they could not but have awaited with extreme interest the result of his labours. It does not appear that this was actually the case. . . . Very little notice was taken of Herschel's special work then, or during the remainder of his life. None helped him, though his researches were manifestly far beyond the strength of any single worker. No comments on his stellar observations, so far as they related to the great problem he was attacking, were made by contemporary astronomers. It was alone, but confidently, that he advanced into the mysterious depths surrounding our Solar System, seeking by the dim light which made the darkness visible to determine, if it might be, the forms dimly discernible within those gloomy wildernesses of space.' [1]

Had Herschel published a book, it would probably have been otherwise. In such case, he would have become known all over Europe as the author of a comprehensive cosmology. Instead of this, his results were only to be found scattered throughout the various volumes of the *Philosophical Transactions* of the Royal Society of London. He wrote obscurely, in an imperfect English style, which fact militated against a proper understanding of his views even by astonomers. We may indeed go as far as to say—paradoxical as it seems—that had Herschel written a book in German, such a book would have attracted a great deal more attention even in Great Britain than his papers in English. Be this as it may, cosmology stood still where he left it in his last paper in

[1] *Our Place Among Infinities*, pp. 258–9.

1818. Not until a quarter of a century after Herschel's death, until Struve published his volume on the subject, was the structure of the Universe tackled directly by a great astronomer.

Indirectly, of course, several important advances had been made in these twenty-five years. A good deal of information had been gleaned concerning the distances and motions of the stars, so that astronomers could at least consider the possibility of using that information as a mode of attack on the main problem. In regard to stellar distances, Herschel, as has been remarked, had no positive information, though his idea that Sirius was distant not less than six and three-quarters light-years shows that his estimate of the scale of interstellar space was not far wide of the mark. His great reflecting telescopes, admirably suited for the purpose of gathering the light of faint stars and nebulae, invaluable as they were for what he liked to call their 'space-penetrating power', were of little use for the measurement of minute quantities such as parallaxes and proper motions. For this the refracting telescope is by far the most serviceable, and just before Herschel's time it was the settled conviction of astronomers that very little progress could be made in the construction of refractors owing to the difficulty of procuring in sufficiently large pieces the flint-glass necessary to correct the unpleasant effect known as chromatic aberration. At the very time, however, when Herschel was at work on his first telescopes, an obscure Swiss optician named Guinand was experimenting on the making of discs of flint and crown glass. His experiments were successful and, his fame having travelled far beyond Switzerland, he was invited to the optical and mechanical institute of Munich. Here Guinand became the instructor of a greater man than himself—the distinguished Fraunhofer, who in 1817 succeeded in making the finest refracting telescope in the world, moving by clockwork and having an object-glass 9½ inches in diameter. Later Fraunhofer

fashioned a still more refined instrument—the heliometer, a kind of divided object-glass micrometer—specially adapted for the measurement of very minute quantities. By a remarkable coincidence these two telescopes passed into the hands of the greatest practical astronomers of the day. The former went to Dorpat, in Russia,[1] where an observatory had been established under the directorship of Friedrich Georg Wilhelm Struve; and the latter to Königsberg, where the still greater Friedrich Wilhelm Bessel was entering on his career as an observer. These were two of the three astronomers who in the thirties of last century simultaneously attacked the problem of stellar distance; the third was Thomas Henderson, a Scotsman, who filled during an all too brief career the posts of Astronomer at the Cape of Good Hope and Astronomer-Royal for Scotland. Struve's value of the parallax of the first-magnitude star Vega did not inspire quite so much confidence as the others. The value for the parallax proved to be too large and the deduced distance too small; but Bessel, with the Königsberg heliometer, succeeded in spanning the great gulf between the Solar System and 61 Cygni, a faint insignificant star of the fifth magnitude. The computed distance announced in December 1838 was about sixty billion miles—a result afterwards confirmed by Otto Struve and Peters and in close accord with the best modern measures. Two months later Henderson announced that as a result of his parallax measures—which were, in point of time, undertaken before those of Bessel or Struve—he had succeeded in measuring the distance of a still nearer star, the bright first-magnitude southern double star, Alpha Centauri. His value was twenty billion miles, increased by later measures to twenty-five billion; and to Henderson belongs the credit of measuring the distance of the nearest star. His parallax of Sirius was likewise slightly too large, and the distance consequently too small. However, later measures by Maclear and

[1] Now in Estonia, and called Tartu.

Peters proved this star to be one of our nearest neighbours, distant about fifty billion miles or 8·6 light-years. Among other stars whose distances were measured or estimated with some degree of accuracy at this early period in the measurement of parallaxes were several faint bodies with considerable proper motions which turned out to be comparatively close at hand, and much nearer than the ordinary first-magnitude star. This proved conclusively that the stars very much differed among themselves in actual luminosity and presumably in size and mass. Even down to the close of the nineteenth century, however, the number of stellar parallaxes measured with any approach to accuracy was far too small to form the basis of any cosmological speculation whatever. All that had been done was that the scale of interstellar space had been ascertained. It was now evident that, just as the unit distance in the Earth-Moon system is a thousand miles and in the Solar System is a million miles, so in the Stellar System the unit is a billion miles.

The data concerning proper motions was, however, considerably less slender. The proper motions of numerous stars had now been measured with some degree of accuracy, and in the early 'forties Mädler, the German astronomer, who succeeded Struve at Dorpat, decided to attack the problem of the construction of the heavens through the avenue of stellar proper motions. The structure of the Solar System suggested that the stars, like the planets, were in motion round a massive centre, and Herschel, in one of his papers on the solar motion, discussed the 'probable existence' of 'a centre of attraction'. Rather than a single body of great magnitude, he thought that 'a great number of stars crowded into one condensed group' might be the centre, and he threw out the suggestion that the Hercules cluster 'must have a very powerful attractive centre of gravity which may be able to keep many far distant celestial bodies in control'. And he further suggested as an alternative that the 'compressed parts

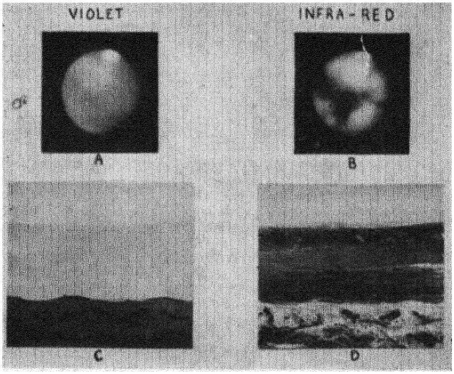
of the Milky Way containing millions of stars may well occasion the sidereal motions we are required to account for'.[1] These were not hypotheses; they were rather ideas which Herschel threw out as he wrote. To the same category belonged Argelander's surmise that the central body of the Stellar System might be located in one of these 'compressed parts' in Perseus. Mädler, however, formulated his hypothesis of a central sun as the outcome of a careful investigation. Assuming with Herschel that the Stellar System is a thin flat system with diameter much greater than its thickness, Mädler concluded that the centre of gravity of such a system must be found somewhere within the limits of the Milky Way and in the northern half of the smaller of the two parts into which the Milky Way divides the heavens. Further, Mädler concluded that the motions in the Stellar System must be fundamentally different from those in the Solar System. In our system the Sun is the dominating body, and the planets nearest to the Sun consequently move much more rapidly than those most distant. In the Stellar System, on the other hand, the mutual attractions of the different stars would cause the stars at the confines of the system to move much more rapidly than those at the centre; indeed, Mädler concluded, stars at the centre must be practically at rest. He therefore undertook to search for a region of very sluggish proper motions, where the stars would be, as it were, held in equilibrium by the mass of the great stellar multitude. He found such a region in the Pleiades, which he concluded to be 'the central group of the entire system of the stars',[2] and he fixed on Alcyone, the chief star of the cluster as the 'central sun' whose headship was determined solely 'by its situation at the point of neutralization of opposing tendencies and consequent rest.'[3] Mädler

[1] *Collected Scientific Papers*, ii, p. 356.
[2] *Die Centralsonne* (*Astronomische Nachrichten*, 1846, no. 567, 257).
[3] Clerke, *History of Astronomy during the Nineteenth Century*, p. 49.

estimated the distance of Alcyone to be 537 light years and computed the Sun's period of revolution to be 18,200,000 years.[1] The hypothesis was decisively rejected by Struve and the younger Herschel, two of the foremost authorities on stellar astronomy. Struve characterized Mädler's procedure as 'much too hazardous'. And Herschel, while holding that such attempts as Mädler's were 'by no means to be discouraged as forerunners of something more decisive',[2] maintained that the centre of gravity could not possibly lie in the Pleiades, a cluster twenty-six degrees away from the galactic plane, out of which plane no such general movement of the stars could take place.

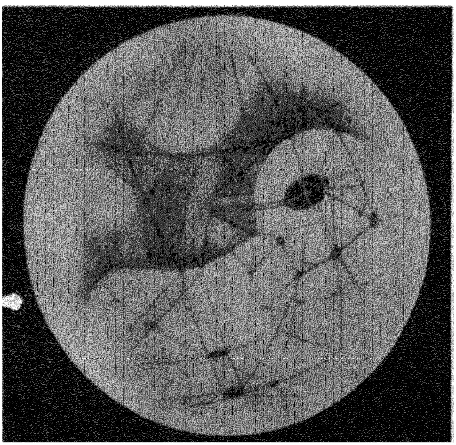
Struve has with justice been called 'the first astronomer after Herschel to make investigations which can be regarded as constituting an important addition to thought on the subject'.[3] Struve was the first prominent astronomer who made a study of Herschel's original papers; he seems to have been better acquainted with them than was Herschel's own son. At all events, after a careful study of these papers he concluded it to be 'incontestable' that the disc-theory of 1785 had been definitely abandoned by its author,[4] and in his own volume, *Studies of Stellar Astronomy—on the Milky Way and on the Distance of the Fixed Stars*, written in French and published in 1847, he outlined his own theory of the Stellar System. Basing his investigation on the star-catalogues of Bessel, Piazzi, and others dealing with 52,199 stars down to the ninth magnitude, he discussed the number of stars in each zone of right ascension. He found that the maximum number of stars per hour was to be found in the two hours of Right Ascension crossed by the Milky Way. The stars down to the ninth magnitude were evidently distributed with reference to the Milky Way. He concluded therefore that the

[1] *Astr. Nach.* 1846, no. 567. 239.
[2] *Outlines of Astronomy*, p. 631.
[3] Newcomb, *The Stars*, p. 234.
[4] *Études d'Astronomie Stellaire*, p. 34 (quoted by Gore, *The Visible Universe*, p. 256).



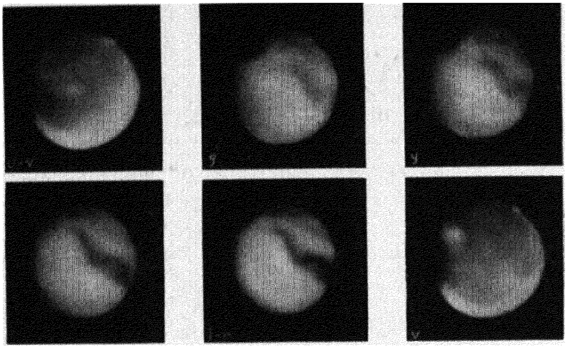
(*a*) PHOTOGRAPHS OF MARS AND OF A TERRESTRIAL LANDSCAPE, WITH ULTRA-VIOLET LIGHT (A AND C) AND INFRA-RED LIGHT (B AND D).

C and D are photographs of San José, taken from the Lick Observatory, Mount Hamilton, $13\frac{1}{2}$ miles away.



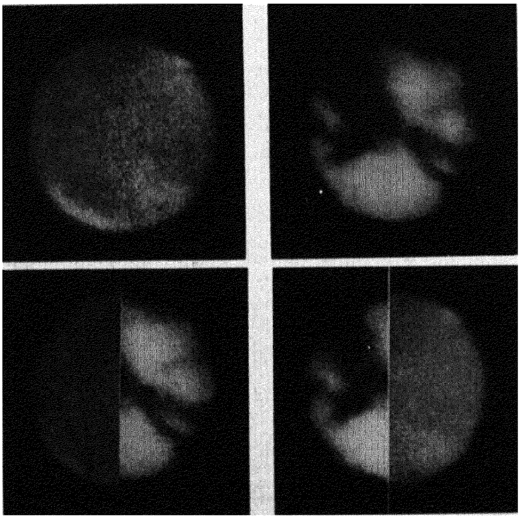
(*b*) DRAWING OF MARS BY LOWELL, SHOWING INTERSECTING CANALS AND OASES.

PLATE VII.



(*a*) PHOTOGRAPHS OF MARS, TAKEN SUCCESSIVELY IN ULTRA-VIOLET, GREEN, YELLOW, RED, INFRA-RED AND VIOLET LIGHT.

The movement of the dark marking across the disc is due to the rotation of Mars. Note the cloud shown in the ultra-violet and violet photographs.



(*b*) PHOTOGRAPHS OF MARS IN ULTRA-VIOLET AND INFRA-RED LIGHT.

In the lower portion, the opposite halves of the two photographs have been placed in juxtaposition, to show the larger size of the ultra-violet image.

PLATE VIII.

stars forming the Stellar System are distributed in the form of a disc, at or near the centre of which the Sun is placed. The stars, however, are not equally distributed. There is a condensation in the distribution of the stars towards a principal diameter of the disc, and Struve assumed that, dividing the disc into bands parallel to this diameter, the star-density diminished on both sides of the diameter and in proportion to distance from the diameter. Although Struve thought the Sun to be nearly central, he found that the line of maximum star-density in his imaginary disc did not pass exactly through the Sun, a fact which indicated that the Sun was not quite in the principal plane.

Struve regarded his disc as strictly finite in thickness, but with a diameter of infinite or indeterminate extent. He misunderstood Herschel's remark in the paper of 1818 that 'when our gauges will no longer resolve the Milky Way into stars, it is not because its nature is ambiguous but because it is fathomless'.[1] For he rendered the English word 'when' into French as 'si', which left the impression that in his opinion Herschel had believed that if the gauges could not resolve the Milky Way, then it must be fathomless. Evidently, as Proctor suggested, Struve translated the English word 'when' as used by Herschel into the German 'wenn', and from thence into the French 'si'. At all events, Struve thought that Herschel's later work had proved the Galaxy to be of practically infinite extension, a view which he adopted. So the Universe as envisaged by Struve was a disc of limited thickness but of infinite, or at least indeterminate extent, in which the stars were condensed in parallel planes, the star-density increasing steadily towards the central plane. It does seem highly improbable, as Gore pointed out many years later, that 'this hypothesis of condensation in parallel planes—a constitution somewhat similar to that of the Earth's atmosphere—should represent the real law of stellar distribution'.[2]

[1] *Collected Scientific Papers*, ii, p. 609. [2] *The Visible Universe*, p. 271.

But the hypothesis was rendered still more improbable by its association with a theory of light-extinction in space. It had been pointed out in 1823 by Olbers of Bremen that if the stars were infinite in number the sky would shine with the brilliance of daylight, as the result of the combined blaze of an endless number of stars; and accordingly he put forward the suggestion that there might be an extinction of light in interstellar space, which would altogether cut off the light from the more distant stars.[1] Struve concluded, therefore, that the light from the vast mass of the distant stars in the plane of the Milky Way was cut off by extinction. 'Admitting the extinction of light', said Struve, 'the brightness of the Milky Way, supposed limitless in extent, is no longer necessarily infinite.'[2] Struve's theory was very strongly criticized by some of his leading contemporaries, including Encke, Grant, and Sir John Herschel. Encke characterized it as based on no fewer than five assumptions, all of which were questionable. Grant urged the formidable objection that if the theory were true the Milky Way ought to present a uniform appearance throughout its course, whereas the reverse is the case.[3] Equally weighty was the objection of Sir John Herschel.

'We are not at liberty to argue that at one part of its circumference our view is limited by this sort of cosmical veil which extinguishes the smaller magnitudes, cuts off the nebulous light of distant masses and closes our view in impenetrable darkness; while at another we are compelled by the clearest evidence telescopes can afford to believe that star-strewn vistas *lie open*, exhausting their powers and stretching out beyond their utmost reach, as is proved by that very phenomenon which the existence of such a veil would render impossible, viz. infinite increase of number and diminution of magnitude, terminating in complete and irresolvable nebulosity.'[4]

[1] Bode's *Jahrbuch*, 1823.
[2] Quoted by Gore, *The Visible Universe*, p. 279.
[3] *History of Physical Astronomy*, p. 582.
[4] *Outlines of Astronomy* (11th ed.), p. 580.

Sir John Herschel's work may be called with justice the sequel to that of his father. William Herschel's gauges were of necessity confined to the northern heavens; John Herschel, during his memorable astronomical expedition to South Africa, obtained a very large number of gauges of the southern heavens, so that the two Herschels may be said to have gauged between them selected areas of the whole sky. The younger Herschel found the law of star-distribution in the southern heavens to be identical with that deduced from the gauges of his father in the northern. But 'it would appear that with an almost exactly similar law of apparent density in the two hemispheres, the southern were somewhat richer in stars than the northern, which may and not improbably does arise from our situation not being precisely in the middle of its thickness, but somewhat nearer to its northern surface'. [1]

Sir John Herschel does not seem to have held any clear-cut theory of the Stellar System; nor does he appear to have been aware, at least in the earlier stages of his career, of any modification in his father's views. At least he gave no hint in his writings of any such radical alteration in the world-view of William Herschel as Struve and, at a later date, Proctor believed to have taken place; which may be taken either as an indication that Sir John Herschel was not intimately acquainted with his father's writings or else that his reading of them convinced him that no radical change really occurred. At all events, in his *Treatise on Astronomy*, published in 1834, he referred briefly to his father's disc-theory without even the slightest hint that it had been abandoned.[2] In the *Outlines* also the disc-theory was likewise reproduced, and the suggestion already referred to, of the Sun's greater proximity to the northern Milky Way, by way of explanation of the greater richness of the southern skies, was in harmony with the disc-theory. But in the same edition of the *Outlines* we find John Herschel considering another

[1] *Outlines of Astronomy*, p. 578. [2] *Treatise on Astronomy*, p. 376.

theory altogether. In his description of the Milky Way in the southern hemisphere, he wrote:

'Throughout all this region its brightness is very striking, and when compared with that of its more northern course already traced, conveys strongly the impression of greater proximity and would almost lead to a belief that our situation as spectators is separated on all sides by a considerable interval from the dense body of stars composing the Galaxy, which in this view of the subject would come to be considered as a flat ring or some other re-entering form of immense and irregular breadth and thickness, within which we are eccentrically situated, nearer to the southern than to the northern part of the circuit.' [1]

This is a diametrically opposite conclusion from that which Herschel deduced from his own and his father's gauges. The first conclusion already referred to, in harmony with the disc-theory, attributed the greater richness of the southern Milky Way to greater star-depth, the Milky Way being viewed as an optical effect, whereas on the second view the Milky Way was a ring of stars surrounding the Stellar System, and the greater richness of the southern skies found an explanation in our greater proximity to the southern portion of the ring. The remarkable fact is that these two irreconcilable views are to be found in the same edition of the same volume.

On the whole, however, it would seem that the younger Herschel inclined to a ring-theory. On this theory the fainter galactic stars were faint not because of excessive distance, but owing to intrinsic faintness. John Herschel thought that in those regions where the Milky Way is clearly resolved into stars 'well separated and seen projected on a black ground', and where presumably 'we look out beyond them into space, the smallest visible stars appear as such, not by reason of excessive distance but of a real inferiority of size or brightness'.[2] Concluding that in the remoter regions of the Galaxy

[1] *Outlines of Astronomy*, p. 571.
[2] Ib., p. 581.

there exist 'innumerable individuals equal in intrinsic light to those which immediately surround us', he deduced for such stars a distance of 2,000 light-years,[1] which would give about 4,000 light-years for the diameter of the Stellar System. On the status of the star-clusters and the nebulae, he does not seem to have had any decisive opinion. At one time he appears to have practically ceased to believe in his father's 'shining fluid',[2] though he lived to see the nebular theory rehabilitated in 1864 by the spectroscope observations of Huggins. He seems to have inclined at the close of his life to the view that all clusters and nebulae were included in one Stellar System.[3] Probably he was influenced by the strong advocacy of this theory by Richard A. Proctor.

Proctor was the first English astronomer to make a close study of William Herschel's papers, and he came to the conclusion, as already mentioned, that Herschel, towards the close of his career, wholly abandoned the disc-theory and that he did not formulate any hypothesis to take its place. It would seem that Proctor was scarcely justified in drawing this conclusion. Certainly, if by the disc-theory we mean the view of the Stellar System as composed of more or less evenly distributed 'insulated' stars, as Herschel called them, then we may say that Herschel abandoned it; but if by the disc-theory we mean, as we generally do, the concept of the Stellar System as a thin disc-shaped system, with its diameter very much greater than its thickness, then Herschel cannot be said to have altered his views. But independently of Herschel's supposed change of opinion, Proctor was led by his own researches to believe that the Milky Way was less of an optical effect than a region of actual clustering where the stars are more closely crowded together than those in the vicinity of

[1] *Outlines of Astronomy*, p. 583. [2] Ib., p. 640.

[3] Letter to R. A. Proctor, 1 August 1869, quoted in Proctor's *Other Suns than Ours*, p. 404. The letters in the appendix of this book are of interest as giving some of Herschel's later views.

the Sun. This conclusion was borne in on Proctor by his own work of star-charting.

During the years 1852 to 1863 Argelander of Bonn, one of the most distinguished of German astronomers, carried through his great *Durchmusterung*, a survey of all the stars down to about the eleventh magnitude. The catalogue and accompanying atlas contained 324,198 stars visible in the northern hemispheres. This survey was afterwards extended by Schönfeld, his successor, to embrace 133,659 southern stars. In 1870 Proctor plotted on a single chart the 324,198 stars included in Argelander's *Durchmusterung*. He found a remarkable connexion between the distribution of the brighter stars and the configuration of the Milky Way—a connexion which on the original disc-theory ought not to exist. 'According to the older theory of William Herschel, we do not come *near* the boundaries of the Stellar Universe with such a telescope as Argelander used. . . . There should be no greater number of stars in the Milky Way zone observed with so small a space-penetrating power than elsewhere.'[1] Yet Proctor found the stars brighter than the sixth magnitude to be markedly crowded on the Milky Way,[2] and he pointed out an intimate association between the rich constellation Orion, as well as the Hyades and Pleiades, and the faint galactic light.[3] But even this was not all that Proctor's star-chart revealed.

'In the very regions where the Herschelian gauges showed the minutest stars to be most crowded, my chart of 324,198 stars shows the stars of the higher orders (down only to the eleventh magnitude) to be so crowded that by their mere aggregation within the mass they show the Milky Way with all its streams and clusterings. This evidence, I venture to affirm, is altogether decisive as to the main question whether large and small stars are really intermixed in many regions of space, or whether the

[1] *Other Suns than Ours*, p. 68. [2] *The Universe of Stars*, p. 199.
[3] Ib., p. 165.

small stars are excessively remote. It is utterly impossible that excessively remote stars could seem to be clustered exactly where relatively near stars are richly spread. This might happen, no doubt, in a single instance, but that it could be repeated over and over again so as to account for all the complicated features seen in my chart of 324,198 stars I maintain to be utterly incredible.'[1]

Proctor therefore believed the brighter and fainter stars of the galactic zone to be inextricably mixed up together. And by this criterion he interpreted Herschel's later observations as indicating that 'when Herschel thought he was penetrating to the extreme limits of the Sidereal System he was in reality only analysing more searchingly an aggregation in which many orders of stars were mixed up. What he failed to do was not, as he supposed, to sound the Galaxy, but to recognize as separate stars the minutest order of orbs included within such aggregations.'[2]

Proctor inclined towards what he called a 'twisted-stream' theory of the Milky Way, which he believed to be composed of comparatively small stars on the confines of the Universe. 'I think', he wrote to Sir John Herschel in 1869, 'that we are bound to look on the stars composing the Milky Way as really minute in comparison with Aldebaran and its like.' Looking on the Milky Way as 'a stream swayed by the leading stars, one seems to get a general conception of its nature according satisfactorily with observed appearances'.[3] Proctor's Universe was strictly limited, containing within it all the nebulae hitherto discovered, 'whether gaseous or stellar, irregular, planetary, ring-formed or elliptic'.[4] He maintained, however, that this view did not reduce the scale of the Stellar Universe. 'I do not', he said, 'draw the nebulae inwards to the star-depths, but I extend the star-depths outwards till they include the nebulae.'[5] At the same time, he did not hold this

[1] *The Universe of Stars*, p. 200.
[2] Ib., p. 217.
[3] *Other Suns than Ours*, p. 414.
[4] *The Universe of Stars*, p. 202.
[5] Ib., p. 202.

view altogether rigidly. In 1869 he thought it 'not improbable that the spiral nebulae are galaxies resembling our own',[1] and in 1886 he suggested that the Magellanic Clouds might be external universes.[2]

Strong evidence in favour of a limited universe was obtained by a test observation made in 1879 by Celoria of Milan. In the course of star-soundings taken at the north galactic pole Celoria found that his small refractor, showing stars barely to the eleventh magnitude, there revealed the same number of stars as Herschel's large reflector, indicating clearly that in the directions of the galactic poles the limit of the system had already been reached. With reference to the general galactic system, Celoria regarded the Milky Way as composed not of one ring but two—a near and comparatively bright ring and one distant and fainter. The distant ring he took to include the stars in Sagitta, Auriga, Monoceros, and Scutum, while the brighter ring was supposed to include the branch of the galactic stream in Ophiuchus and a belt of bright stars extending round the heavens.[3]

Proctor's conclusion as to the aggregation of the brighter stars in the galactic stream was confirmed by G. V. Schiaparelli of Milan in the course of a study of the distribution of the stars visible to the unaided eye.[4] Dividing the sky into thirty-six zones and 1,800 areas, Schiaparelli compared the density of each area and constructed a series of planispheres on which the star-density was marked. The result was to show an indisputable crowding of the lucid stars towards the galactic zone. As Newcomb put it, Schiaparelli's planispheres showed 'that were the cloud-forms which make up the Milky Way invisible to us, we should still be able to mark out its

[1] *The Universe of Stars*, p. 76.

[2] *Knowledge*, March 1886.

[3] Gore, *The Stellar Heavens*, p. 109. A fuller account is given in the biographical sketch of Celoria in my *Astronomers of To-day*, pp. 109–11.

[4] *Sulla Distributione Apparente delle Stelle visibili ad Occhio Nudo* (Brera Observatory Publications, Milan 34, 1889).

course by the crowding of the lucid stars towards it. As a matter of interest I have traced out the central line of the darker shaded portions of the planispheres as if they were the Galaxy itself.' [1]

The conclusion was tested with reference to the brightest magnitudes by Gore, in the course of a careful investigation. He found that of 32 stars brighter than the second magnitude 12 lie on the Milky Way or 'on faint nebulous light connected with it'; of those brighter than the third magnitude 33 out of 99, and of those brighter than the fourth 73 out of 262—'a grand total of 118 stars out of 392 above the fourth magnitude'. From an enumeration of all the stars shown in the atlas of the German astronomer Heis, Gore found the number to be 1,186. 'Now the total number of objects shown by Heis (excluding variable stars, clusters, and nebulae) is from his catalogue 5,356, so that for all the stars visible to the naked eye in this country (down to 6·3 magnitude) the percentage of stars on the Milky Way is 22·1, or about one and a half times that due to its area.' [2] Gore believed the Milky Way to be a 'ring-shaped cluster', the light of which 'is reduced to nebulosity by immensity of distance'; [3] and the late Miss Clerke wrote: 'The Milky Way so far as can be immediately discerned is a rifted and irregular ring' which 'marks the equator of a vast globe'. [4] This 'vast globe' Gore estimated to have a diameter of 4,600 times the distance of the nearest star—about 20,000 light-years. [5] This was an estimate more generous than the majority of astronomers would have been willing to allow.

The German astronomer Seeliger carried through from 1884 to 1898 what Newcomb called 'the most thorough study of the distribution of the great mass of stars relative to the

[1] *The Stars*, p. 246. [2] *The Stellar Heavens*, p. 106.
[3] *Concise Knowledge Astronomy*, pp. 564–5.
[4] *The System of the Stars* (2nd ed.), p. 373.
[5] *The Visible Universe*, p. 320.

galactic plane'.[1] This was based on the star-gauges of the Herschels, the *Durchmusterung* of Argelander and Schönfeld, and the counts of Celoria. Dividing the sky into zones by small circles parallel to the Milky Way, Seeliger found a gradual increase in star-density from either galactic pole to the galactic equator. These results really disposed of the ring-theory, because if the Galaxy were a ring of stars surrounding a star-sphere, the increase in the average number of stars per field would be not gradual but sudden near the boundary of the ring. 'The Milky Way', said Seeliger, 'is no mere local phenomenon but is closely connected with the entire constitution of our Stellar System.'[2] At the same time Seeliger seems to have regarded the Milky Way phenomenon as due to stellar condensation as well as to star-depth, which is of course partly true. Rejecting, like Schiaparelli, the theory of any extinction of light in interstellar space, Seeliger envisaged the Stellar Universe as finite in extent and about 18,000 light-years in diameter.[3]

At the close of his exhaustive volume on *The Stars*, published in 1901, Newcomb in a guarded and cautious way summed up the conclusions which appeared most probable at the close of the century. 'That collection of stars which we call the Universe is limited in extent.' This was accepted as axiomatic at the close of the nineteenth century and still is, so far as the main Stellar System is concerned. This view, however, Newcomb said, 'does not preclude the possibility that far outside of our Universe there may be collections of stars of which we know nothing.'[4] Newcomb believed that the faintest stars seen with the more powerful telescopes 'are not for the most part more distant than those a grade brighter, but are mostly stars of less luminosity situate in the same

[1] *The Stars*, p. 247. [2] Quoted by Newcomb, *The Stars*, p. 250.

[3] Biography of Seeliger in my *Astronomers of To-day*, p. 183.

[4] *The Stars*, p. 319. Gore agreed with this. Cf. *The Visible Universe*, p. 322.

Star-Field in Canis Minor

regions'. At the same time he accepted Seeliger's view that the Universe is of considerably greater extension in the plane of the Galaxy than towards the poles—a view which indicated a kind of a return towards the Herschelian cosmology.

The boundary of the system, Newcomb believed, 'is somewhat indefinite and irregular. The parallax at the boundary is probably nowhere greater than 0·001″ and may be much less. The time required for light to pass over the corresponding interval is more than three thousand years.'[1] This gave the diameter of the system as 6,000 light-years, for Newcomb, in keeping with other astronomers, assumed that the Sun was very nearly in a central position. He was aware, however, that this assumption might be conceivably without foundation, and in the form of a question he used words which may be called prophetic. 'One reflection may occur to the thinking reader as he sees these reasons for deeming our position in the Universe to be a central one. Ptolemy showed by evidence which from his standpoint looked as sound as that which we have cited that the Earth was fixed in the centre of the Universe. May we not be the victims of some fallacy as he was?'[2]

[1] *The Stars*, p. 319. [2] Ib., p. 318.

IV

TWENTIETH-CENTURY PROGRESS

So far as astronomy is concerned, the twentieth century may already lay claim to the name of the 'wonderful century'. In no other period of equal length has the rate of progress been so rapid as in the three decades which have elapsed since the century dawned. In no branch of the science has the rate of progress been so great as in that relating to the structure of the Stellar System.

In their attack on the main problem Herschel and his nineteenth-century successors were in the main dependent on the data which had been accumulated concerning the distribution of the stars; which, although of great value, were not very extensive. The latter half of the last century, however, witnessed the accumulation of a great mass of material relating to stellar positions, and therefore of motions. Schönfeld's extension of Argelander's *Durchmusterung* to a part of the southern sky was the first of a number of important enterprises undertaken with a view to acquiring a more exhaustive knowledge of the entire sky. Gould, the American astronomer, who for many years directed the Observatory at Cordova in Argentina, constructed in 1879 a catalogue of 8,198 southern stars and seven years later an additional 32,448. The Scottish astronomer Sir David Gill in 1882 applied photography for the first time to the work of star-charting, and from 1885 to 1889 he extended the *Durchmusterung* from the point where Schönfeld left it to the southern celestial pole. J. C. Kapteyn of Groningen completed in 1900 the reduction of the plates and the formation of a catalogue. By this time a much more ambitious work was in progress, namely, the *Astrographic Chart and Catalogue*, the joint work of eighteen observatories in various countries. The mass of material thus

accumulated proved somewhat unwieldy, and in 1906 Kapteyn proposed his famous 'plan of selected areas'. His project, of which he lived to see the adoption, was the construction for 206 areas distributed uniformly over the sky of catalogues giving magnitudes, parallaxes, proper motions and radial velocities down to the extreme limits of faintness. Various observatories co-operated with the great Dutch astronomer in this highly important piece of work. Simultaneously, the Mount Wilson Observatory carried through important counts of fainter stars, and the Harvard Observatory brought to completion the *Henry Draper Catalogue of Stellar Spectra*. Since the beginning of the present century, in addition to this accumulation of data, a sufficient number of proper motions—both across and in the line of sight—have been determined to serve as a means of attack on the chief problem of cosmology; while several new methods of measuring stellar distances have been devised which have led to the determination of the distance of a large number of stars and also to the measurement of the distances of very distant objects.

Studies of proper motion had resulted, in the latter half of the nineteenth century, in the recognition of what are called 'common proper motions'. When Mädler in his search for a centre for the Stellar System came upon a region of sluggish proper motion in the constellation Taurus, what he actually discovered was not the motion of the stars round Alcyone, but the fact of a common proper motion among the stars of Taurus. The significance of this discovery was not realized at the time, and the discovery of the common proper motion of two or more stars was made at a considerably later period. In 1870 Proctor found, after a careful examination of the seven bright stars of 'the Plough', in Ursa Major, that five of these had a common proper motion. 'Whereas Alpha and Eta are moving much as they would if the Sun's motion were alone in question, the other five are all moving at one

and the same rate . . . in almost exactly the same direction.'[1] He found also that two fainter stars shared in this 'drift'; and he came to the conclusion that the five bright and the two faint stars actually formed what he called a 'drifting set'—the odds being 'half a million to one' that these common proper motions were not the result of chance. When Huggins by means of the spectroscope measured the motions of the five stars in the line of sight and found all five to be receding at the same rate, the odds against chance coincidence became overwhelming. Many years afterwards, in 1909, Hertszprung of Potsdam showed that other eight bright stars, including Sirius, are component members of this moving cluster.

Proctor detected in addition another instance of star-drift. He pointed out the true significance of the region of sluggish proper motion in Taurus, on which Mädler had based his theory of a central sun. As in the case of the Ursa Major group, Proctor's discovery of the moving cluster in Taurus was verified many years later by the American astronomer Lewis Boss. Similar to Proctor's two 'drifting sets' are two moving clusters discovered early in the present century. Kapteyn, Eddington, and Benjamin Boss independently detected a moving cluster in Perseus, some of the stars of which form a conspicuous visual group; while the bright stars in Orion, with the probable exception of Betelgeux, undoubtedly constitute a physical system.[2] Instances of pairs of stars having a common proper motion were detected by Flammarion in 1877. He found that the bright first-magnitude star Regulus and a faint eighth-magnitude star known as Lalande 19,749, from its number in that astronomer's catalogue, had a common drift through space,[3] and that two double stars in Cygnus likewise had an identical proper motion.[4] Schönfeld in 1881 drew attention to two ninth-

[1] *The Universe of Stars*, p. 151.

[2] Eddington, *Stellar Movements and the Structure of the Universe*, p. 63.

[3] *Comptes Rendus*, 5 November 1877. [4] Ib. lxxxv, p. 783.

magnitude stars in Libra, separated by a wide space and yet moving at exactly the same rate in the same direction.[1]

While these were recognized as genuine instances of star-drift, the opinion prevailed at the close of the nineteenth century that the motions of the great mass of the stars were at random. Indeed, determinations of the position of the solar apex from Herschel's time downwards had been based on the assumption that this was so. Gradually it began to dawn on astronomers that perhaps the assumption had been made too hastily; they began to see that the position of the apex in the sky varied according to the stars used in each investigation. In 1895 the German astronomer Kobold, latterly director of the Kiel Observatory, after an investigation of the discordant positions assigned to the apex, expressed the view that the results could be reconciled on the assumption that the individual motions of the stars are not at random, but take place in the plane of the Milky Way 'some in the direct sense and others in the retrograde sense; the motion of the Sun occurring in a plane which makes an angle of 17° with the plane of the Milky Way.' [2]

Nine years later Kapteyn of Groningen showed conclusively that the motions of the stars are not at random. After eliminating the parallactic components from the proper motions of the bright stars in the catalogue of Bradley, revised by Auwers, Kapteyn found that the motions of the stars fall into two favoured directions—opposite to each other—in the galactic plane, and that the number of stars drifting in the one direction is half as large again as the number drifting in the other. A. S. Eddington of Cambridge showed in 1906 and Sir F. W. Dyson of Greenwich in 1908 that this phenomenon of star-streaming is not confined to the brightest stars, but is discernible even in the case of stars invisible to

[1] Clerke, *The System of the Stars*, p. 329.

[2] *Astr. Nach.*, pp. 137, 393 (1895), quoted Campbell, *Stellar Motions*, p. 140.

the unaided eye, down to the ninth magnitude. Kapteyn, Eddington, and Dyson dealt in these investigations only with the proper motions across the line of sight; later, however, W. S. Adams of Mount Wilson Observatory, in collaboration with Kapteyn himself, found that the radial motions of the stars, spectrographically determined, likewise indicated the existence of a preferential drift in two opposite directions. With the exception of a group which seems to be virtually at rest, practically all the nearer stars would appear to show this drift; but as early as 1911 Eddington sounded a note of caution as to assuming that all the stars in the Stellar System belong to one or other of these streams. 'The two star-streams probably involve at least half a million of the stars around us; but there has never been any evidence that they prevail in the extremely remote parts.' [1]

Dr. Herbert Dingle rightly warns us not to imagine that 'all the stars are moving in the directions of their respective streams. As well as the stream motion they have their individual movements which may be in any direction. Nevertheless the general streaming tendency is decidedly marked. The stars in each stream may be compared, with some reservations, to a number of children on a road; the individual children may have widely divergent lines of movement but the general tendency is towards the school.'[2] Kapteyn and his co-workers naturally interpreted the discovery as indicating that at least the nearby stars were composed of groups drifting through each other, 'like two swarms of insects moving in opposite directions through the same region of space.'[3] Efforts were made by Schwarzschild, Turner, and others to reconcile what seemed to be evidence of duality with the unity of the Stellar System which theory seems to demand. In recent years, however, it has become more and more evident that star-streaming is a local phenomenon.

[1] *Observatory* (1911), vol. 34, p. 357.
[2] *Modern Astrophysics*, p. 98. [3] Ib., p. 99.

Still another 'law' of stellar motion was detected early in the century as a result of the amassing of such information concerning the motions—angular and radial—of the stars of different spectral types. The invention of the spectroscope in the middle of last century was indeed of epoch-making importance in stellar astronomy. A year after its application to the Sun, Donati of Florence turned a small spectroscope to the stars, but was able only to fix the positions of the more important lines in the spectra of the brighter stars. A few years later, William Huggins and Angelo Secchi, in London and Rome respectively, began a systematic spectroscopic study of the brighter stars. Besides intensive analysis of the spectra of some of these, Huggins first succeeded in measuring the motions of stars in the line of sight by means of Doppler's principle. His work in this department was largely pioneer work, carried out under very great difficulties, and more substantial results were achieved by Vogel of Potsdam, who in 1887 applied photography for the first time to the measurement of radial motions. Later the American astronomers Keeler, Campbell, Frost, and Adams measured the velocity of thousands of stars in the line of sight with remarkable accuracy, so that by the end of the first decade of the century a vast amount of information was available.

While Huggins and his successors concentrated on an intensive study of particular stars, Secchi made a comprehensive spectroscopic survey of the sky visible from Rome. He passed in review four thousand stars and classified them into four distinct types. The first or Sirian type was represented by Sirius, Vega, Altair, and other blue-white stars, whose spectra were chiefly characterized by the lines of hydrogen. The second or solar type embraced the yellow stars such as the Sun, Capella, Arcturus, and Pollux, with spectra characterized by innumerable metallic lines. The third type included red stars such as Betelgeux and Antares, with strong absorption bands in their spectra, while the fourth

type consisted of rare and faint red stars, also with broad absorption bands. In 1867 a fifth type was added by Wolf and Rayet, astronomers of the Paris Observatory. These stars, comparatively few in number, were seen to have spectra with bright lines in place of dark.

Secchi's classification was revised by Vogel in 1874 and later in 1895, when he differentiated between the helium and hydrogen stars. The classifications both of Secchi and Vogel, however, were swallowed up in the 'Draper classification', carried through at Harvard College Observatory under the direction of E. C. Pickering. In this classification the various classes of stars are designated by the letters OBAFGKMN. Type O consists of Wolf-Rayet stars, type B of the helium or 'Orion' stars, type A of the Sirian stars, and types F, G, and K of the stars more or less like the Sun, while types M and N include the two classes of red stars. About 99 per cent. of all the stars were brought within the sweep of this classification. For a considerable time it was believed that, representing as it did the order of decreasing temperature, it likewise served as an index to the course of stellar evolution. Hence stars of type B were called 'early-type' stars, while stars of class M were said to be of 'late type'. Although very few astronomers now believe the Harvard sequence to represent an evolutionary progression, these names are still retained as a matter of convenience.

Even before the close of the century astronomers were in a position to compare the distribution and motions of the stars of various spectral types. E. C. Pickering in 1891 summarized what was known on this matter in these words: 'It appears that the number of stars of the second and third type is nearly the same in the Milky Way as in other parts of the sky. Considering, therefore, only the stars whose spectra resemble that of the Sun, we should find them nearly equally distributed in the sky.'[1] Stars of Secchi's first type,

[1] *Harvard Annals*, vol. 26, p. 152.

on the other hand, were found by Pickering to be much more numerous in and near to the galactic circle than in other parts of the sky. In the case of the A stars Pickering found them to be twice as numerous on the Milky Way as outside of it, and in the case of the B stars more than four times as numerous. In 1892 W. H. S. Monck of Dublin pointed out that the stars of Secchi's second type had on the average larger proper motions than those of the first. This was confirmed by Kapteyn, and for a time was thought by him to indicate the greater proximity of the second-type stars. When a sufficient number of radial motions had been measured, it became apparent that these indicated the same phenomenon. Frost and Adams in 1903 showed that twenty stars of the Orion type had remarkably small linear velocities; and when Kapteyn detected the two star-streams further evidence came to light. As Eddington puts it: 'It was found that the "spread" of the motions of the type I stars was less wide than those of type II, the former following much more closely the directions of the star-streams. Though other interpretations were conceivable, this seemed to indicate that the individual motions of the type I stars were smaller than those of type II.'[1] In 1910 it was announced independently by Kapteyn and Campbell that on the average the radial velocities of the stars of the so-called later types were greater than those of the earlier types, and that in fact the average linear velocity increased from one type to another. 'The progression of average velocity with advancing spectral type is clear and unmistakable.'[2]

At that time the great majority of astronomers believed that the Harvard sequence did represent an evolutionary progression and the discovery by Kapteyn and Campbell was interpreted as meaning that as a star grew older it moved faster. A few years later, however, Professor H. N. Russell

[1] *Stellar Movements and the Structure of the Universe*, p. 155.
[2] Campbell, *Stellar Motions*, p. 200.

of B type stars. Hence a B star, however faint it may appear, must have a certain minimum absolute magnitude, which enables a minimum distance to be fixed.

Still more potent for the purpose of taking deep space-soundings is the method based on what is called the 'period-luminosity law' of the variable stars known as Cepheids. This was detected by the American astronomer, Miss Leavitt, in the course of a study of the small Magellanic Cloud. As Shapley, to whom is due the application of the law to measurement of great distances, has remarked:

'For twenty-five Cepheid variable stars of the small Magellanic Cloud the length of the period of variation depends on the apparent brightness. . . . As the variables in the Cloud are all at essentially the same distance from the Earth, the correlation is actually between intrinsic brightness and period of variation. . . . As soon as variable star observers have derived the period and apparent magnitude, the absolute magnitude may be read from the period-luminosity curve and the distance computed. . . . Cepheid variables, therefore, as well as eclipsing stars, permit us to go out much farther into space than we had hitherto gone.' [1]

It has also become possible, largely through the work of F. H. Seares, the American astronomer, to ascertain the hypothetical spectra of very faint stars. The photographic plate is more sensitive than the eye to certain wave-lengths of light; there is thus a difference between the photographic and the visual magnitude of a star. This difference is called the colour-index and is due to the star's colour. The faint stars are therefore divided into colour classes and, as Seares points out, 'by virtue of the intimate relation between colour and spectrum, they indicate the spectral class within narrow limits.' [2]

As a result of the application of these methods, the astronomers of the early twentieth century have been much

[1] *Star-Clusters and the Structure of the Universe* (reprint from *Scientia*), pp. 8–10.

[2] *Adolfo Stahl Lectures in Astronomy*, p. 224.

more favourably placed than their predecessors of the late nineteenth century for a frontal attack on the problem of the structure of the Universe. Foremost among these investigators must be mentioned Kapteyn and van Rhijn, Charlier, Shapley, and Seares. Of these astronomers, the two Dutchmen attempted to outline the Stellar System by working from within outwards; while the two Americans and the Swede have chosen rather to begin at the circumference by fixing the distances of very distant objects.

In an important paper, published in 1916, Dr. C. L. V. Charlier of Lund, the distinguished Swedish astronomer, summarized the results of his attack on the problem by the method of absolute magnitude. Starting on the assumption that the B stars do not differ much one from another in absolute magnitude, Charlier made determinations of the distance of these stars down to the fifth magnitude. He found that 'the luminosity of these stars is indeed so great that a star of this type situated—so far as can be concluded—at the limits of our Stellar Universe is scarcely fainter than the eighth magnitude. We are thus in the position to get, with the help of the B stars, what might appropriately be called a skeleton image of the Milky Way.'[1] The diameter of the system marked out by these B type stars Charlier found to be about 1,000 parsecs, or roughly 3,000 light-years. The Sun he found to be not quite central. 'The centre of this cluster, which may be assumed to coincide with the centre of our Stellar Universe, is situated in the constellation Carina.'[2] The distance from the centre he estimated at 88 parsecs or about 264 light-years. The identification of the system marked out by the B-type stars with the Stellar Universe was an unwarranted assumption, as Charlier later realized.[3]

[1] *Meddelanden från Lunds Astronomiska Observatorium*, series 2, 14, p. 103. [2] Ib., p. 104.

[3] Shapley, *The Scale of the Universe, Bulletin of National Research Council*, No. 11, p. 174.

For about a quarter of a century the late Dr. J. C. Kapteyn, perhaps the greatest cosmologist after Herschel, was engaged in an attempt to formulate a tenable cosmology on the basis of the ascertained parallaxes, proper motions, and luminosities of the stars. During the latter portion of his career he worked in collaboration with Dr. P. J. van Rhijn, who latterly succeeded him in his Groningen chair. In 1920 and 1922 Kapteyn and van Rhijn were in a position to formulate such a cosmological scheme. Kapteyn calculated two mathematical expressions, the first of which represented the average parallax of stars of any given apparent magnitude, and the second the average parallax of stars of given apparent magnitude and proper motion. By means of these expressions he was able to derive the total number of stars in any specified volume of space, of any assigned absolute magnitude. This is called the luminosity function, and, according to it, for every star of absolute magnitude -5 there are 90 of absolute magnitude $-2{\cdot}5$ and 3,300 of absolute magnitude 0. Kapteyn showed that the 'luminosity curve' derived from the function could be applied to any range of absolute magnitude and that it sufficed therefore to determine the star-density at any place in space.

Working outwards from the Sun as centre, Kapteyn and van Rhijn found that the stars thinned out gradually and that the Stellar System was limited in extent. 'We have not yet studied the question of the limits to which our results for the density are fairly reliable,' they wrote in 1920, 'but there is hardly a doubt that we can adopt them as a good approximation up to at least 1,500 parsecs. In the direction of the pole of the Galaxy this brings us to what many will be inclined to take as practically the limit of the system. At least the density at that distance cannot be 1/200 of that near the Sun. In any direction along the plane of the Milky Way, on the contrary, this same limit must be eight times more distant.'[1]

[1] *Mount Wilson Contribution*, No. 188, p. 16.

Taking the Sun as central and a parsec as approximately three light-years, this gives for the extent of the Universe a thickness of 9,000 light-years and a diameter of 72,000. These dimensions are very much greater than had been assumed for the Stellar System either by Gore, Newcomb, or Seeliger at the close of the nineteenth century.

Kapteyn was well aware that the assumption that the stellar centre passed in or near the Sun was an assumption only. In his last paper in 1922 he calculated that the Sun was 650 parsecs, or roughly 2,000 light-years from the centre of the system, which he found to be in the southern constellation Vela. Assuming the stars to be rotating along the main axis of the Stellar System, Kapteyn concluded that at distances greater than 2,000 parsecs the systematic velocity of the stars was nearly constant, namely, about 19·5 km. per second. 'If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km. per second, we have a quantitative explanation of the phenomenon of star-streaming where the relative velocity is also in the plane of the Milky Way and about 40 km. per second.'[1] Thus Kapteyn found room in his cosmological scheme for the phenomenon of star-streaming which his own researches first brought to light. 'Kapteyn's universe', says Dr. Dingle, 'includes star-streaming as a possible if not an inevitable phenomenon.'[2]

In 1914 Dr. Harlow Shapley, then an assistant astronomer at Mount Wilson Observatory, now director of Harvard College Observatory, commenced his series of studies on the colours and magnitudes in stellar clusters by means of the 60-inch reflector. The clusters studied included both the compact globular clusters—such as that in Hercules—far from the galactic plane, and the open galactic clusters which are undoubtedly part and parcel of our Stellar System. His

[1] *Mount Wilson Contribution*, No. 230, p. 1.
[2] *Modern Astrophysics*, p. 365.

estimated distance of the Hercules cluster, derived from its variable stars, luminosity-curves, and the average brightness of certain colour-groups, was 100,000 light-years. So great a distance for so bright a cluster was not expected, and Shapley's determination came upon the astronomical world in the nature of a surprise. The distance was subsequently reduced to 36,000 light-years, but even this was sufficiently large to suggest that the Universe was a good deal larger than contemporary astronomers believed.

Shapley's observations on the open clusters and the galactic star-clouds, however, afforded still stronger evidence for a much larger Stellar System than astronomers had been prepared to admit. In the open cluster M 11 and in neighbouring galactic star-fields Shapley discovered a number of stars with negative colour indices—that is to say, very faint blue stars—of the thirteenth to the fifteenth magnitudes. 'The presence of small and negative colour indices in the galactic clouds indicates either that the stars are at a great distance or that they are not similar in luminosity to the bright stars near the Sun. . . . The first alternative is decidedly preferable.'[1] For according to Russell's theoretical researches a star cannot reach the B stage unless of great mass; B stars are unlikely to be dwarfs.[2] Shapley concluded that the distance of the cluster-stars, presumably giants, must be of the order of 15,000 light-years; and that the neighbouring star-clouds must be at least equally distant. 'The wide dispersion in magnitude of both blue and red stars suggests a similarly great distance for the neighbouring galactic star-clouds. It suggests that the extent of the stellar clouds in the line of sight is relatively very great—in fact, the depth may be as great as, or greater than, the distance to the nearer boundary.'[3]

[1] *Mount Wilson Communication*, No. 37, p. 3.

[2] There are, of course, stars known as 'white dwarfs'; these are not observed in any considerable number because of faintness, but are probably fairly numerous in a given volume of space.

[3] *Mount Wilson Contribution*, No. 133, p. 11.

In other parts of the Milky Way, 'the study of stars in clusters indicated analogous conditions and the conviction grew that the galactic system had an extent of at least 15,000 parsecs along its plane'.[1]

By 1918 Shapley had succeeded by means of several independent methods in fixing the positions in space of eighty-six globular clusters. He found that these formed a great ellipsoidal system, divided by the galactic plane—forty-three clusters lying on either side. He defined these globular clusters as cosmic units, dependent on the greater Stellar System, and he found the equatorial plane of the system of globular clusters to coincide with that of the galactic system. 'Remembering that their equatorial planes evidently are identical, we naturally infer that the galactic system and the assemblage of globular clusters are co-extensive and that the centre of the two systems may be the same.'[2] He found the centre of gravity of the system of globular clusters, and presumably therefore of the Stellar System, amid the dense star-clouds of the Galaxy in Sagittarius, 60,000 light-years from the Sun. He got strong confirmatory evidence of this in the discovery by the Dutch astronomer Nort of Utrecht, from a study of the Harvard map, that the star-density in the direction of the southern Milky Way clouds is four or five times greater than in the northern,[3] and in the conclusion reached by Chapman and Melotte from their study of the plates obtained by Franklin-Adams in his photographic surveys. One plate, according to Chapman and Melotte,

'covers the Sagittarius region of the Milky Way and the star clouds on limited portions of it are so thick that in the case of twelve out of twenty-five areas counted on it, it was found impossible to count every star shown; the images of the faintest stars in these regions merged into one another forming a continuous grey back-

[1] *Mount Wilson Contribution*, No. 157, p. 6.
[2] *Star-Clusters and the Structure of the Universe*, p. 14.
[3] *Astronomical Researches*, Utrecht Observatory, 8, 113 (1917).

ground. On every other plate of the Franklin-Adams series even the faintest images shown were separate and distinct and the counts included all stars visible. The extreme richness of the Sagittarius region may be judged of, then, when it is noticed that the incomplete counts on it show far more stars than are found in any other part of the Milky Way.' [1]

Further evidence of the much greater depth of the system in the direction of Sagittarius was obtained by Shapley in 1923 in his study of the distribution of the stars according to spectral type. He found that the fainter stars of classes Ma, Mb, and Mc are much more numerous in the direction of Sagittarius. Further, 'in the direction of Taurus there is but one-half the average number of long-period variables and in the opposite direction of Sagittarius there is twice the average number'.[2] Novae, planetary nebulae, Cepheids and O-type stars, all of which show a marked concentration towards the galactic plane, are also of greater frequency in the direction of Sagittarius.[3]

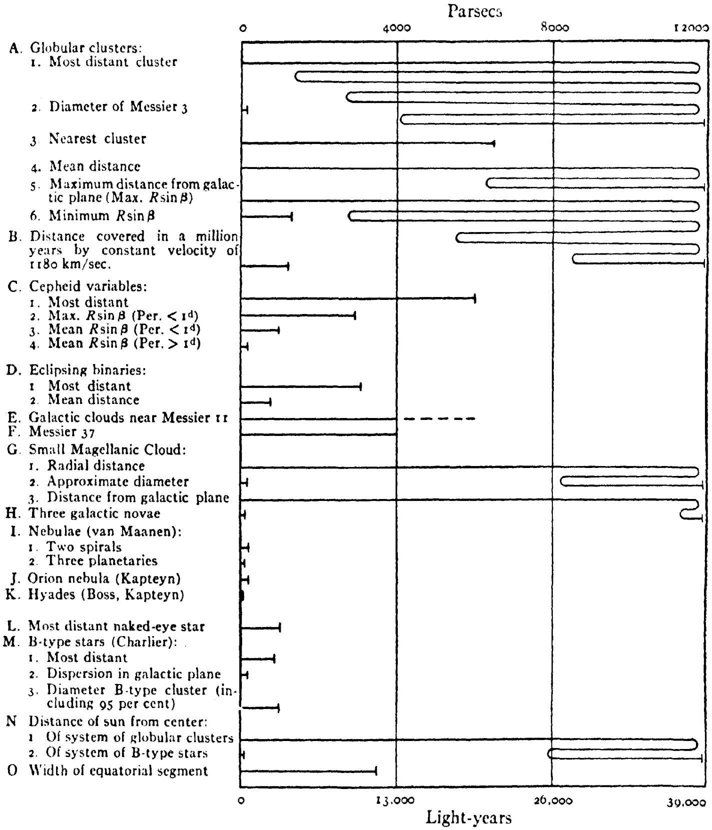
Still further confirmation of Shapley's position for the galactic centre was forthcoming in the work on stellar motions of the Norwegian astronomer, Gustav Strömberg, of Mount Wilson, and the Swedish astronomers, Knut Lundmark of Upsala, and Bertil Lindblad of Lund. Dr. Strömberg detected in 1923 an asymmetry of motion in the galactic plane 'nearly perpendicular to the direction toward the centre of the system of globular clusters as determined by Shapley'. 'The velocity of translation' of our local system is about 300 km. per second, and 'it is possible that the local system moves round the centre of the larger system with this velocity.'[4] Dr. Lundmark showed in 1925 that the motion of our Sun is directed towards a point (galactic longitude

[1] *Memoirs, R.A.S.*, 60, Part IV, p. 168 (1915).

[2] *Harvard Circular* 245, p. 6.

[3] *Summary of a Study of Stellar Distribution, Harvard Reprint* from *Proc. American Academy*, p. 218.

[4] *Mount Wilson Contribution*, No. 275, p. 22.



Distances in the Stellar System according to Dr. Shapley

75°) 'nearly at right angles to the direction where modern conceptions of the Universe place the centre of our galactic system. . . . This may indicate a rotation of our local cluster in the plane of the Milky Way round the Sagittarius region.'[1] Dr. Lindblad in 1927 concluded that the axis of rotation of the Stellar System is in the direction of galactic longitude 330°. 'The direction of the axis of rotation points very nearly towards the centre of distribution of the system of globular clusters according to Shapley's investigations.'[2] The Dutch astronomer Dr. Jan H. Oort of Leyden in 1927 found evidence of 'non-uniform rotation of the galactic system round a very distant centre',[3] probably coincident with the same point.[4] The conclusions of Lindblad and Oort have been confirmed by Dr. J. S. Plaskett of Ottawa, who regards the coincidence as definitely established.[5]

It may be accepted, then, that the Sun is far from the centre of the Stellar System;[6] and the Stellar System is very much greater than has ever been supposed in volume—'a hundred thousand times as large as we formerly believed it to be',[7] and at least 300,000 light-years in diameter. The system is vastly more extended in the galactic plane than in the direction of the poles. 'A thin central stratum of the galactic segment contains almost every star that has been seen or has been photographed for our catalogues. This stratum of stars apparently deviates less than two thousand light-years from the galactic plane.'[8] Thus, according to Shapley in 1920, the Stellar System is 4,000 light-years in

[1] *Monthly Notices, R.A.S.*, lxxxv, p. 869. [2] Ib., lxxxviii, p. 553.

[3] *Bulletin of Astronomical Institutes of the Netherlands*, iii, No. 120, p. 280. [4] Ib., iv, No. 132, pp. 79, 89.

[5] *Monthly Notices, R.A.S.*, lxxxviii, p. 400.

[6] Easton, the Dutch astronomer, seems to have been alone among astronomers before Shapley's investigations, in placing the Sun at a distance from the centre, which he believed to be among the star-clouds of Cygnus. *Astrophysical Journal*, vol. 37, p. 105 (1908).

[7] Shapley, *Star-Clusters and the Structure of the Universe*, p. 28.

[8] Ib., p. 26.

thickness. A few years later Shapley was willing to admit a greater thickness. 'The majority of the stars are found within five thousand light-years of the plane, but occasionally peculiar variable stars and other objects of high velocity are found five or ten times this distance from the central plane.'[1] The Stellar System, in Shapley's cosmology, as in Herschel's, is a thin flat disc. 'The phenomenon of the Milky Way', according to Shapley, 'is largely an optical one. Although the existence of local and occasionally very extensive condensations of Milky Way stars is not denied, the conception of a narrow encircling ring is abandoned. The Milky Way girdle is chiefly a matter of star-depth and its long recognized weakness between longitudes 90° and 180° is now taken to be a reflection of the eccentric position of the Sun.'[2] The galactic system, said Shapley in 1928, is 'an irregularly circular and much flattened system'—'a conglomerate of single stars, groups of stars, clusters, and great star-clouds, seriously obscured in certain regions by nebulosity'.[3] We have come back to a very great extent to Herschel's later concept of the Stellar System as a greatly extended thin disc, composed both of independent stars and of star-clusters.

Substantial confirmation of Shapley's world-view was obtained in 1928 by Dr. Frederick H. Seares, of Mount Wilson, by his recent studies in stellar distribution. Seares, approaching the subject from a different angle, that of the space density, or the distribution of the stars, finds the position of maximum stellar density to be in close agreement with the centre derived by Shapley from the globular clusters. Although the space density in Sagittarius is considerable, it is not sufficiently great; 'a central condensation of relatively high density' is, Seares shows, to be expected in an organization like the Stellar System'.[4] Accordingly he assumes that the central condensation is invisible to us, cut off by the

[1] *Starlight*, p. 130. [2] *Mount Wilson Contribution*, No. 157, p. 7.
[3] *Harvard Reprint from Proc. Nat. Acad. of Sciences*, vol. xiv, No. 11, pp. 825–6. [4] *Mount Wilson Contribution*, No. 347, p. 49.

presence of the huge dark cosmical clouds which modern astronomers invoke to explain the strange dark places in the sky and the rifts in the Milky Way. 'The diameter of the system is large—80,000 to 90,000 parsecs, if it may be regarded as coextensive with the system of globular clusters; at least 80,000 parsecs if the absolute magnitudes of normal B 0–B 2 stars may be assigned to the faint blue stars of the Milky Way; and at least 60,000 parsecs if, as seems probable, stars in the direction of the anti-centre occur at distances as great as 10,000 parsecs.'[1] Seares' maximum estimate—90,000 parsecs, is not far off Shapley's value—100,000 parsecs, or 300,000 light-years.

In discussing the close agreement between his value for the position of the central condensation and that obtained by Shapley, Seares remarked that the agreement of Shapley's value of the galactic longitude of the centre 'with that derived from the star counts is close and any further hesitation in accepting Shapley's value of the distance arises from a feeling that the ill-defined and widely scattered collection of a hundred or so clusters may not be closely concentric with the system of the stars',[2] and Dr. Shapley is himself conscious of the necessity of discovering the extent of the Galaxy and the distance of the centre 'by direct measurement, instead of continuing to base our estimates largely on the distribution of the globular clusters'.[3] From his study of the absolute luminosities of cluster type variables in the 240 Harvard Milky Way variable star fields, Shapley measured in 1928 the distance of the rich star cloud in Scorpio and Ophiuchus in which these variables are situated. He finds the brighter variables on the nearer side of the cloud to be placed at distances of 21,000 to 30,000 light-years, and the centre of the cloud itself to be 47,000 light-years away.

[1] *Mount Wilson Contribution*, No. 347, p. 54. [2] Ib., p. 51.

[3] *Harvard Reprint* from *Proc. Nat. Acad. of Sciences*, vol. xiv, No. 11, p. 826.

'It thus appears', says Shapley, 'that in exploring the rich star cloud in Scorpio and Ophiuchus . . . we have been measuring a portion of the central nucleus of the galactic system. Lanes of obscuring nebulosity cut off the star cloud . . . from the richer regions across the galactic equator in Sagittarius and Scorpio; but there can be little doubt that behind the dark nebulosity the star-clouds are dense and continuous. A massive galactic nucleus is indicated at a distance of nearly fifty thousand light-years. Its diameter perpendicular to the galactic equator is some thirty degrees, corresponding to 25,000 light-years, but its extent along the Milky Way and in the line of sight is less certain. In no other part is the Milky Way so broad or rich as in this central region.'[1]

Thus the conclusion reached by Seares, that the massive central nucleus is for ever hidden from our view behind obscuring nebulosities, is confirmed by the independent work of Shapley.

That the Stellar System, though finite, is of very great extent along the plane is borne out not only by recent measures of stellar distance but by recent studies of stellar distribution. During the present century elaborate investigations have been made by Kapteyn, Chapman and Melotte, and Seares and van Rhijn. Kapteyn in 1908 discussed all the available data—such as the star-gauges of the Herschels Seeliger, Celoria, and others, and found a very marked concentration of the fainter stars to the galactic plane. Some years later, Chapman and Melotte, by an independent investigation, found values of star-density in general agreement with Kapteyn's values down to the ninth magnitude. On the other hand, for the lower magnitudes their values differed very greatly from those of Kapteyn. Thus while Kapteyn found the ratio of star-density at galactic latitude 5° to that at 80° to be 44·8, Chapman and Melotte found it to be only 4·3. The question was finally set at rest by Seares and van Rhijn, the results of whose elaborate investigation

[1] *Harvard Reprint* from *Proc. Nat. Acad. of Sciences*, vol. xiv, No. 11, p. 833.

were made known in 1925. As a result of their work, Kapteyn's conclusions were abundantly confirmed. Seares and van Rhijn found that 'at the fourth magnitude the ratio of the numbers of stars per square degree at latitudes 0° and 90° is 3·5. At the twenty-first photographic magnitude the totals per square degree in the Milky Way and at the Pole are 73,600 and 1,667 respectively, with a ratio of 44. To the same limit the integrated total for the whole sky is 890,000,000. To the twentieth visual magnitude the corresponding total is 1,000,000,000';[1] and the possible total in the Stellar System is estimated to be about 30,000 million. 'The separate totals for the latitude intervals 0–20°, 20–40°, and 40–90° emphasize again the importance of the Milky Way as a structural feature of the system. They show that 95 per cent. of the stars are within 20° of the galactic circle, or, stated otherwise, that regions centred on the poles of the Milky Way comprising two-thirds of the sky include but 5 per cent. of the stars belonging to our system.'[2]

In this vast system of possibly 30,000 million stars the Sun fills the humble role of a dwarf star, nowhere near the centre and displaced about 33 parsecs, or roughly a hundred light-years north of its principal plane.[3] As Newcomb surmised might be the case, the astronomers of the nineteenth century were victims of a fallacy when they assumed the Sun's position in the Stellar System to be central. What they had really ascertained was that the Sun was near the centre of a local cluster and they had naturally but mistakenly identified that cluster with the Universe.

[1] *Mount Wilson Communication*, No. 92, p. 6. [2] Ib., p. 7.

[3] Gerasimovič and Luyten, *Harvard Reprint* from *Proc. Nat. Acad. Sciences*, 13, p. 390.

V

THE LOCAL CLUSTER

IN the course of his forty years of strenuous thinking on the structure of the Universe, William Herschel was led from the hypothesis of the Stellar System as consisting of millions of 'insulated' stars distributed with some approach to uniformity to the concept of the Stellar System as made up of a number of clustering groups. And he suggested somewhat vaguely in 1802 that the Sun and the stars in 'that part of the heavens which is immediately around us' might form 'a very extensive system'.[1] But this was a mere suggestion, and the idea of a local cluster may be said to have had its origin in the mind of his son. In 1847 the younger Herschel, in his description of the course of the Milky Way, remarked that in the interval between Eta Argus and Alpha of the Southern Cross

'the galactic circle, or medial line of the Milky Way, may be considered as crossed by that zone of large stars which is marked out by the brilliant constellation of Orion, the bright stars of Canis Minor and almost all the more conspicuous stars of Argo, the Cross, the Centaur, Lupus, and Scorpio. A great circle passing through Epsilon Orionis and Alpha Crucis will mark out the axis of the zone in question, whose inclination to the galactic circle is therefore about twenty degrees and whose appearance would lead us to suspect that our nearest neighbours in the Stellar System—if really such—form part of a subordinate sheet or stratum, deviating to that extent from parallelism to the general mass which, seen projected on the heavens, forms the Milky Way.'[2]

This was a definite suggestion that the stars in the vicinity of the Sun might possibly be grouped together as a kind of local cluster within the greater Stellar System. But like many other fertile ideas which dropped from Herschel's keen mind,

[1] *Collected Scientific Papers*, ii, p. 359.
[2] *Cape Observations*, p. 385.

this idea of a local cluster attracted little further attention, even from its author. It was not until more than thirty years had elapsed that it was again put forward, and supported by a not inconsiderable weight of evidence, by the distinguished American astronomer, Benjamin A. Gould. As the result of his observations of the southern skies, Gould came to the conclusion that 'a belt or stream of bright stars appears to girdle the heavens very nearly in a great circle, which intersects the Milky Way at about the points of its highest declination and forms with it an angle not far from twenty degrees; the southern node being near the margin of the Cross and the northern in Cassiopeia'. This belt, said Gould, includes the bright stars of Orion, Canis Major, Argo, Crux, Centaurus, Lupus, and part of Scorpio, as well as Lyra, Cygnus, Cepheus, Cassiopeia, Perseus, and Taurus. While Herschel interpreted this belt of bright stars as indicative of the existence of a 'subordinate sheet or stratum', Gould deduced from it the existence of a local cluster. 'I cannot avoid the conviction that our own system forms part of a small cluster distinct from the vast organization of that which forms the Milky Way and of a flattened and somewhat bifid form. This cluster may perhaps be comparable with the Pleiades, since by a crude estimate it would seem to consist of less than 500 stars.'[1]

This view met with but little acceptance among the astronomers who were engaged in the study of stellar distribution and the structure of the Universe. Emphasis had been laid by Proctor on the crowding of the brighter stars on the Milky Way and the general view was that the plane of concentration for the brighter stars was identical with that for the fainter—the medial plane of the galactic stream. 'I cannot see', wrote Gore in 1893, 'that Dr. Gould's "belt of bright stars" is at all strikingly marked—at least in the northern hemisphere. . . . The apparent connection of the bright stars with the

[1] *Uranometria Argentina*, p. 159.

Milky Way itself seems to me almost as clearly defined.'[1] Newcomb concluded that 'it would not be safe, however, to assume that the existence of this belt results from anything but the chance distribution of the few bright stars which form it.'[2] Gould's hypothesis was thus rejected by the leading astronomers of his day.

In the course of his study of the parallactic motions of the stars Kapteyn discovered that the stars of Secchi's first spectral type have on the average smaller proper motions than those of the second type. Evidently, this is capable of one or other of two explanations. Either the stars of the second type move more rapidly than those of the first, or the stars of the first type are more distant. Kapteyn considered the second of these explanations to be much more probable, and Newcomb agreed with him. 'The near vicinity of the Sun contains nearly exclusively stars of the second type; with increasing distance the proportion of the number of stars of the first type to that of the second grows gradually.'[3] From this conclusion Kapteyn was led to a further conclusion, namely, that these stars of the solar type comprised, along with the Sun, a subordinate system within the greater Stellar System. This, which he termed the solar cluster, was considered to be roughly spherical in shape, not unlike the Andromeda nebula. In 1902, however, Kapteyn withdrew this interpretation and abandoned the cluster theory, while maintaining that second-type stars are on the average nearer to the Sun than first-type stars of equal brightness. At a later stage of his career he was to discover, independently of Campbell, the progressive increase of speed with advancing spectral type, and thus to weaken still more considerably

[1] *The Visible Universe*, p. 159. Mr. Gore admitted, however, that 'the position of Orion, the Hyades, the Pleiades, and Lyra seems in favour of Dr. Gould's theory'.

[2] *The Stars*, p. 243.

[3] Quoted in biography of Kapteyn in my *Astronomers of To-Day*, p. 189.

the assumption of a preponderance of yellow stars in the solar vicinity.

As mentioned in the last lecture, Charlier of Lund attempted to fathom the Stellar System by means of the B-type stars; and in 1916 he announced that these stars formed a well-defined and flattened cluster with centre of gravity in the constellation Carina. Charlier computed this cluster to have a diameter of about 4,000 light-years; at this stage he believed it to be more or less co-extensive with the Universe. He even called it a 'skeleton image of the Milky Way'. Certainly there was a slight discrepancy between the position of the galactic pole as found from his group of B-stars and the pole as found from the Milky Way itself; but this discrepancy he treated as, on the whole, without significance.

In 1918 Shapley, from his study of the globular clusters, found in the case of the system outlined by the globular clusters a centre of gravity in the constellation Sagittarius. This was a very different centre from that fixed on by Charlier from his study of the 'skeleton image' of the Galaxy, and suggested that Charlier and Shapley had been dealing with distinctive systems. Further, Shapley remarked that 'if the difference in the positions of the two poles be real, an inclination of the central plane of the B-type system to the Galaxy is indicated'.[1] In the course of his investigations of different types of celestial bodies Shapley found not one plane, but two.

'The two planes do not coincide and this lack of coincidence becomes at once the strongest proof of the actuality of a distinct local organization. The open clusters, the globular clusters, the galactic novae, the Cepheid variables, the star-clouds—classes of objects extending far beyond the bounds of the solar domain—all define one and the same plane; they all appear symmetrically distributed on each side of the generally accepted galactic circle.

[1] *Mount Wilson Contribution*, No. 157, p. 19.

But we now find that the brighter stars of spectral types B and A (and we infer that the same holds for all stars of the local cluster) are symmetrically organized about a plane that is inclined between ten and fifteen degrees to the galactic circle.'[1]

The important effect of the Sun's position in this local cluster, not far from the central plane is that the bright stars of the cluster are projected on the sky along a narrow belt inclined to the main galactic stream. This 'secondary galaxy', Shapley remarked, is nearly coincident with Gould's belt of bright stars.

But this local cluster, in Shapley's view, does not contain all the stars in the solar neighbourhood. Besides the cluster stars, Shapley recognized what he called 'field stars'—stars which do not differ in any essential particular from those of the general galactic system. The Sun was believed by Shapley in 1918 to be 'evidently a field star', and was thought to be 'at some distance laterally from the centre of the cluster and a few parsecs above its central line of symmetry'.[2] Among 'cluster stars' Shapley included nearly all the B-stars and the majority of the A-stars above the seventh magnitude, along with 'a large percentage' of the redder stars within three or four hundred parsecs from the Sun. Among the 'field stars' he grouped 'very few B's, a small percentage of A's, and possibly a majority of the redder spectral types', along with Cepheid variables, Wolf-Rayet stars, the Ursa Major group, planetary nebulae, and stars of very high velocity. Shapley concluded that the cluster stars are moving as a dynamical group through the field stars and that from this motion the phenomenon of star-streaming arises. As seen from the Solar System, 'the local cluster, if in motion, must inevitably

[1] *Star-Clusters and the Structure of the Universe*, pp. 32–3.

[2] *Mount Wilson Contribution*, No. 157, p. 17. Two years later Shapley said that 'it is not clear now and probably can never be indisputably determined whether our Sun is a field star or a member of the cluster' (*Star-Clusters and the Structure of the Universe*, p. 36). Cf. Shapley, *Starlight*, p. 119.

produce star-streaming analagous to that observed; hence it is a natural assumption that the recorded systematic motions of the local stars are due wholly to such a cause'.[1] If Shapley's explanation be correct, the phenomenon of star-streaming, as Eddington surmised soon after the original discovery, is confined to the stars in the vicinity of the Sun. This surmise, and incidentally also the existence of the local cluster itself, was confirmed by Strömberg's discovery that stars of the spectral types F, G, and K have motions related to the same centre as that determined by Charlier for the B-type stars.[2]

As early as 1920 Shapley was able to make a tentative estimate of the extent of the local cluster. He found faint blue stars to be concentrated to the plane of the secondary Galaxy at a distance of 1,200 light-years from the Sun; accordingly he concluded that the local cluster is very flat and probably much larger than the ordinary 'open clusters' of the galactic segment. He concluded also from his study of the B-stars that 'the galactic field is continuous in the immediate environs of the local cluster—that the latter is not a large group or cloud distinctly and distantly isolated in space from other stellar regions'.[3] In 1919 Shapley showed that down to the seventh magnitude the B-stars were concentrated to the plane of the local cluster, but that for fainter stars the galactic equator 'definitely established itself as the central circle for B-type stars'.[4] In 1922, after his appointment to succeed E. C. Pickering as director of Harvard College Observatory, Shapley examined the stars of class A with a view to ascertaining whether they also were concentrated to two planes. Discussing 2,450 bright A-stars, he found confirmatory evidence of the existence of the cluster. 'The deviation from the galactic plane is of the same character

[1] *Mount Wilson Contribution*, No. 157, p. 24.

[2] Strömberg in the paper in which he announced his discovery assumed this centre to be the galactic centre (*Mount Wilson Contribution*, No. 144, p. 29); but this was before Shapley's rediscovery of the local cluster.

[3] *Mount Wilson Communication*, No. 64, p. 6. [4] Ib., p. 6.

as that shown by the B-stars, but it is less pronounced.'[1] The fainter stars of class A0, however, showed 'a high concentration to the primary galactic circle, and no certain trace of the secondary'.[2] Evidence for the existence of the local cluster was also secured by Dr. Edwin P. Hubble of Mount Wilson, in his study of the distribution of the nebulae, completed in 1922. The distribution of the diffuse galactic nebulae, Hubble found, is 'not a simple concentration along the galactic plane. . . . Two distinct belts are defined—the Milky Way and a belt inclined at about 20° to the Milky Way'.[3] From a study of the distribution of clusters other than the globular variety, Charlier found that this is nearly identical with that of the B-stars;[4] and Mr. Peter Doig, the Scottish astronomer, plotting the galactic latitudes and longitudes of forty-nine open clusters, showed that the 'nodes' of this system of open clusters is 'about the same as for the B-stars'.[5]

The recent work of Dr. F. H. Seares has shown the local cluster to be of even greater extent and importance than Dr. Shapley surmised in 1918. Seares, in his study of the distribution of the stars, found that attempts to locate the centre of the main Stellar System by ignoring the possibility of the existence of a local aggregation 'lead to contradictory results which strengthen the conclusion that the cluster cannot be ignored'.[6] By a different road, therefore, Seares is led to the same conclusion as Shapley. Indeed, in his scheme the cluster bulks even more largely than in Shapley's. Apparently it includes most of the bright stars and 'is of dominating influence in determining the space density near

[1] *Harvard Circular* 229, p. 4.

[2] *Summary of a Study of Stellar Distribution, Harvard Reprint* from *Proc. Amer. Acad.*, vol. 59, p. 222.

[3] *Mount Wilson Contribution*, No. 241, p. 8.

[4] *Meddelanden Lund Astr. Obs.*, 2, 14, p. 103; cf. Doig, *Stellar Astronomy*, p. 132.

[5] *B. A. A. Journal*, vol. 36, p. 118.

[6] *Mount Wilson Contribution*, No. 347, p. 2.

the Sun'.[1] Its influence is traceable at least to the fifteenth magnitude. Though the mean distance of fifteenth-magnitude stars is not well known, Seares computes that stars belonging to the cluster occur at distances of 3,000 parsecs—roughly 9,000 light-years—from the Sun. Assuming that the Sun is not far from the centre of the local cluster, we may compute the cluster's dimensions as of the order of 18,000 light-years. The dimensions assigned by Seares to the local cluster are thus equal to those computed by Seeliger for the entire Stellar System at the close of the last century.

This local cluster, so important that the great majority of astronomers formerly identified it with the Universe, is not, however, in any sense a unique system. The greater galactic system would appear to be an aggregation of 'local' clusters. 'The galactic system', says Shapley, 'is an organization of stars and star clouds, nebulae and clusters. The star-clouds in the Milky Way are sub-organizations in the general galactic system, each containing still smaller systems.'[2] Just as the local cluster is inextricably mixed up with the stars of the general galactic system which Herschel used to speak of as 'insulated', so 'the open clusters are intermingled with the non-cluster stars of the galactic stratum'.[3]

According to Lindblad the sub-systems of which the galactic system is composed are each in dynamical equilibrium and rotating about a common axis perpendicular to the galactic plane. The system with the highest speed of rotation, that of the Milky Way clouds, will be the most flattened towards the plane. The stars composing this system will be closely crowded and will have small individual velocities; the orbital motions will be nearly circular. Other sub-systems will have different degrees of flattening and the stars composing them will have larger residual velocities.

[1] *Mount Wilson Contribution*, No. 347, p. 30.

[2] *Starlight*, p. 118.

[3] Shapley, *Mount Wilson Communication*, No. 62, p. 5.

On this view, 'the Sun and surrounding stars lie in a flattened system with a high speed of rotation'.[1]

The local cluster and presumably the so-called open clusters, as well as the dense star-clouds of the Milky Way, do not by any means form a homogeneous system. The local cluster includes within its bounds many subordinate aggregations—groups such as the Pleiades, the Taurus cluster, the Ursa Major system and the group of bright Orion stars. All these sub-organizations exist within the local system, which is itself a sub-organization within the greater Universe. The extreme heterogeneity of the galactic system and its subordinate clusters lends strong support to Shapley's idea, to which reference is made in a later lecture, that the Stellar Universe as we know it has been formed in the course of ages by the union of several more or less compact clusters and the absorption by the resultant system of great mass of all the other clusters which came within its sphere of influence.

[1] Plaskett, *Monthly Notices R. A. S.*, lxxxviii. 395.

VI

THE STATUS OF THE NEBULAE

THE two brightest nebulae are just visible to the unaided eye, and one of them, the Great Nebula in Andromeda, was referred to in a description of the heavens written in 905 by the Persian astronomer Al-Sufi,[1] and appears on a chart of the constellation Andromeda constructed in Holland about 1500. After the invention of the telescope it was rediscovered in 1612 by Simon Mayer, one of the earliest telescopic observers, who described it as resembling 'a candle shining through horn'.[2] In 1656 Huyghens drew attention to

'one phenomenon among the fixed stars worthy of mention which, so far as I know, has hitherto been noticed by no one, and, indeed, cannot be well observed except with large telescopes. In the sword of Orion are three stars quite close together. In 1656 as I chanced to be viewing the middle one of these with the telescope, instead of a single star, twelve showed themselves (a not uncommon circumstance). Three of these almost touched each other, and with four others shone through a nebula, so that the space around them seemed far brighter than the rest of the heavens, which was entirely clear and appeared quite black, the effect being that of an opening in the sky through which a brighter region was visible.'[3]

That these strange objects were openings in the sky seems to have been the prevalent opinion in the seventeenth century. But Halley believed the Andromeda nebula to represent 'nothing else but the light coming from an extraordinary

[1] Gore, *The Worlds of Space*, p. 198.

[2] Clerke, *History of Astronomy during the Nineteenth Century*, p. 25.

[3] *Systema Saturna*, quoted by Newcomb, *The Stars*, p. 178. The nebula had been noticed casually by a Swiss observer, Cysat of Lucerne, in 1618.

great space in the ether, through which a lucid medium is diffused that shines with its own proper lustre'.[1]

During the seventeenth and eighteenth centuries, the name nebula was applied to all cloudy spots; and in 1755 a list of these was drawn up by the French astronomer Lacaille. Further and more comprehensive lists were drawn up in 1771 and 1782 by Messier, another French astronomer. Messier's chief astronomical interest was the discovery of comets, and he catalogued all the nebulae known to him, in order that he might not fall into the error of believing himself to have detected a new comet when he had merely re-observed a nebula. His second catalogue contained 103 entries, and comprised, besides true nebulae, many objects which we now know to be star-clusters.

That all nebulae were star-clusters in disguise, irresolvable because of their great distances, was the original theory of William Herschel, who commenced the observation of these objects just after the publication of Messier's catalogue. With much greater telescopic powers than the French astronomer had at his command, Herschel undertook a systematic examination of the nebulae, and, as he himself expressed it, 'saw with the greatest pleasure that most of the nebulae which I had the opportunity of examining in proper situations yielded to the force of my light and power and were resolved into stars'.[2] After completing a survey of Messier's nebulae Herschel commenced to search for new nebulae. A catalogue drawn up in 1786 contained a thousand new nebulae —including star-clusters—and in a second catalogue in 1789 there were an equal number of entries. Thirteen years later a third catalogue was drawn up containing five hundred nebulae and kindred objects. After his death his sister and assistant, Caroline Herschel, combined all these nebulae into one catalogue and arranged them into zones. This catalogue

[1] Quoted by Gore, *The Worlds of Space*, p. 198.
[2] *Collected Scientific Papers*, i, p. 158.

The 'North America' Nebula in Cygnus

formed the foundation of John Herschel's *General Catalogue*, published in 1864, which contained the places of 5,089 nebulae and clusters, mostly discovered by him and by his father.

As has already been pointed out, Herschel at first believed that all nebulae were clusters of stars, and on this assumption he based his theory of the Stellar System as one universe among others. In the course of his career, his own observations first threw doubt upon this assumption and finally discredited it, and by the close of his career he recognized the division of the nebulae into two distinct classes, those composed of a mysterious 'shining fluid'—the primeval chaos out of which, he believed, the suns and worlds of the future would be evolved—and those which were simply star-clusters too far away to be resolved into their component stars. In 1811 he attempted to arrange the nebulae of the former type in an evolutionary sequence, 'assorting them into as many classes as will be required to produce the most gradual affinity between the individuals contained in any one class with those contained in that which precedes and that which follows it'.[1] But for some time neither his nebular theory nor, for that matter, the theory of Laplace, attracted a great deal of attention.

Soon after Herschel's death a reaction set in against his later views and in favour of his earlier. Astronomers began to think that he had been over-hasty in invoking the existence of a shining fluid to explain his unresolved nebulosities. Within twenty years of his death a great increase had taken place in telescopic power. The colossal reflector of the Irish nobleman, Lord Rosse, and the 15-inch refractors of Pulkova in Russia, and Harvard, U.S.A., seemed to give evidence against Herschel's shining fluid. By means of these telescopes a number of nebulae which Herschel had believed to be gaseous were resolved into stars, and accordingly the erron-

[1] *Collected Scientific Papers*, ii, p. 460.

eous conclusion was drawn that because some had been resolved all would in time be resolved. Finally, a number of stars were detected in the Orion nebula by means of the Rosse reflector and the Harvard refractor, and it was believed that the nebula was in process of being resolved into stars. 'The resolution of this nebula', said the American astronomer Olmsted, 'has been the signal for the renunciation of Herschel's nebular hypothesis.'[1] Sir John Herschel, while admitting the nebular theory to be 'a physical conception of processes which may yet, for aught we know, have formed part of that mysterious chain of causes and effects antecedent to the existence of separate self-luminous solid bodies',[2] stated that the probability that all nebulae are resolvable 'has almost been converted into a certainty by the magnificent reflecting telescope constructed by Lord Rosse, of six feet in aperture, which has resolved or rendered resolvable multitudes of nebulae which had resisted all inferior powers'.[3]

With the invention of the spectroscope came the opportunity for settling the problem once and for all. According to the principles of spectrum analysis, enunciated by Kirchhoff, a cluster of stars at a great distance ought to show a continuous spectrum, while a mass of gaseous matter should show a spectrum characterized by bright lines. The test observation was made by Huggins on the 29th of August 1864. On that evening, wrote Huggins thirty years later:

'I directed the spectroscope for the first time to a planetary nebulae in Draco. The reader may now be able to picture to himself to some extent the feeling of excited suspense, mingled with a degree of awe, with which after a few moments of hesitation I put my eye to the spectroscope. Was I not about to look into a secret place of creation? I looked into the spectroscope. No

[1] Appendix to Mitchell's *Orbs of Heaven*, p. 302.

[2] *Outlines of Astronomy* (ed. of 1849), p. 641.

[3] Ib., p. 639. Lord Rosse himself, however, pointed out that it was unsafe from his observations to conclude that all nebulae were remote clusters (Huggins, *Scientific Papers*, p. 106).

spectrum such as I expected! A single bright line only. . . . The riddle of the nebulae was solved. The answer which had come to us in the light read, Not an aggregation of stars, but a luminous gas.' [1]

By 1866 Huggins had examined the spectra of seventy nebulae and had ascertained nearly one-third of these, including the great Orion nebula, to be genuinely gaseous. On the other hand, he found that in the case of nebulae like that of Andromeda 'the strong bright line spectrum is absent'.[2] Even so, however, Huggins evidently believed that nebulae of this type were akin to those showing unambiguous spectra. Commenting in 1889 on the famous photograph of the Andromeda nebula secured by Isaac Roberts, Huggins said that this photograph 'shows a planetary system at a somewhat advanced stage of evolution; already several planets have been thrown off, and the central gaseous mass has condensed to a moderate size as compared with the dimensions it must have had before any planets had been formed'.[3]

Huggins was careful to point out the effect on cosmological thought of the demonstrated gaseous nature of many of the nebulae. On the cluster theory, nebulae such as that in Orion must of necessity be placed at enormous distances from the Sun. Thus Olmsted estimated the Orion nebula to be 60,000 light-years distant.[4] But Huggins remarked that 'the opinions which have been entertained of the enormous distances of the nebulae, since these have been founded upon the supposed extent of remoteness at which stars of considerable brightness would cease to be separately visible in our telescope, must now be given up in reference at least to those of the nebulae the matter of which has been established

[1] Article on 'The New Astronomy', reprinted in *The Scientific Papers of Sir William Huggins*, p. 106.

[2] Ib., p. 172.

[3] *Scientific Papers of Sir William Huggins*, p. 173.

[4] *Orbs of Heaven*, p. 302. Olmsted's estimate was a hundred times greater than modern determinators.

to be gaseous'.[1] The proof that gaseous nebulae did exist and the inference that all nebulae were more or less chaotic masses and at least non-stellar in their composition resulted in a shrinkage of the Universe as mirrored in the mind of man. The Stellar System as conceived by Proctor was a much more homely affair than that of Herschel. While careful not to commit himself to the opinion that all nebulae are gaseous,[2] he did embrace the view that all the nebulae 'gaseous or stellar, irregular, planetary, ring-formed or elliptic' were 'part and parcel' of the Stellar System.[3]

Gradually astronomers were driven back towards Herschel's view that there were in reality two main classes of nebulae, generally different one from the other. Despite Dr. Isaac Roberts' photograph of the Andromeda nebula and the interpretation which astronomers generally placed upon that photograph, it became more and more evident that it was different in kind from the Orion nebula. Scheiner at Potsdam secured in January 1899 a spectrograph of the Andromeda nebula, in which dark lines similar to the Fraunhofer lines in the solar spectrum were clearly visible;[4] and this nebula is but the brightest member of a very large class. Later research has shown it to be a spiral nebula. Further, the two classes of nebulae were seen to differ not only in spectrum but in distribution. While the spiral, 'spindle', and 'globular' nebulae shun the galactic zone altogether, the gaseous nebulae—irregular and planetary—have long been known to be strongly concentrated towards the Milky Way. Accordingly, Dr. Edwin Hubble of Mount Wilson has divided the nebulae into two distinct classes—the galactic and non-galactic—the former comprising the irregular and planetary

[1] *Scientific Papers of Sir William Huggins*, p. 119.

[2] 'The spectroscope tells us . . . that many of the nebulae are composed of luminous gas' (*The Universe of Stars*, p. 75).

[3] *The Universe of Stars*, p. 202.

[4] *Astr. Nach.*, 3549; Clerke, *Problems in Astrophysics*, p. 20.

nebulae, and the latter the spiral, the spindle, and the globular types.

In his study of the distribution of the galactic nebulae, Hubble discovered that the large planetary nebulae are fairly uniformly distributed over the sky, while the smaller members of this class show a pronounced galactic concentration. Assuming that the apparent diameters and the magnitudes of the central stars give a clue to distance, he reaches the conclusion that 'when real distributions are determined the vertical deviations from the galactic plane will prove to be relatively small'.[1] In the case of the diffuse nebulae their distribution is not a mere concentration to the galactic plane; they congregate towards two distinct belts—the Milky Way itself and a belt inclined to it by about 20°. This latter seems to have the same nodal points as the group of bright helium stars which form the outline of Shapley's local cluster. The double concentration can have but one interpretation and one only. Some of the diffuse nebulae belong to the local cluster, such as the Orion nebula, 600 light-years away. Others are far away in distant Milky Way clouds. It would seem that between the local cluster and the star-clouds beyond conspicuous nebulae are practically non-existent.

Hubble's discovery of the relation between the spectra of the diffuse nebulae and the involved stars has largely modified our view of the nature of nebulae. Stars involved in diffuse nebulae having continuous spectra, and presumably shining by reflected light, are always of type B or later; while stars involved in nebulae with emission spectra are almost invariably of earlier type than B. 'This intimate relation between spectral type of nebula and of involved stars', Hubble maintains, 'raises a presumption that one is a consequence of the other. It seems more reasonable to place the active agency in the relatively dense and exceedingly hot stars than in the nebulosity, and this leads to the suggestion that nebulosity

[1] *Mount Wilson Contribution*, No. 241, p. 8.

is made luminous by radiation of some sort from stars in certain physical states'.[1] Evidently the emission nebulae are excited to luminosity by the radiation of the hottest stars, while the cooler stars do not seem capable of this and accordingly the nebulous matter surrounding them shines by reflected light.

That some nebulae shine by reflected light has been surmised for many years; no other explanation could be advanced to explain the vagaries of a nebula in Taurus discovered in 1852 by Hind of London and proved by the German astronomer D'Arrest to be variable in light. Kapteyn in 1901, in order to account for the apparent expansion of the nebula surrounding Nova Persei, suggested that the nebula was actually dark and that the seeming expansion was due to the progressive motion of the light from the nova causing more and more of the nebula to be illuminated.[2] In 1912 Dr. V. M. Slipher demonstrated for the first time that a nebula could shine by reflected light. Astronomers had been familiar since 1859 with wisps of nebulosity clinging round the stars in the Pleiades; and the photographs of Max Wolf and others had shown the cluster to be enveloped in nebulosity. In December 1912 Slipher, photographing the spectrum of the nebula, made the unexpected discovery that 'the nebula shines by light which is a true copy of that of the neighbouring star Meope and of the other bright stars of the Pleiades', and he drew the obvious conclusion that 'the Pleiades nebula shines by reflected light'.[3] In 1916 spectrograms were obtained of diffuse nebulosity surrounding the star Rho Ophiuchi. 'It appears', wrote Slipher, 'that the spectrum of this nebula is continuous and so far as can be judged from this weak plate it is like that of Rho Ophiuchi, about which this nebula clusters. . . . The indications are that this nebula is shining by reflected light, as was found to be true of the

[1] *Mount Wilson Contribution*, No. 241, p. 28.
[2] *Astr. Nach.*, No. 3756. [3] *Lowell Observatory Bulletin*, No. 55.

Region of the Nebula Rho Ophiuchi

nebula in the Pleiades'. Slipher noted also the suggestive fact that 'in both these regions of the sky faint stars are conspicuously deficient in numbers. The type of spectrum conforms to the view that the scarcity of stars in these and certain other regions is due to light absorption by nebulae which may otherwise be invisible'.[1]

Dark starless spaces in the sky have been familiar to astronomers ever since Herschel's pioneering surveys. His sister Caroline, writing to her nephew Sir John Herschel in 1834, referred to such voids. 'It is not clusters of stars I want you to discover in the body of the Scorpion (or thereabout) for that does not answer my expectations, remembering having once heard your father, after a long awful silence, exclaim: "Hier ist Wahrhaftig ein Loch in Himmel".'[2] This was the interpretation which he put on his observations of such celestial vacuities; and this was the view which prevailed down to the close of the nineteenth century. 'My own opinion', said Gore, who made a close study of these phenomena, 'is that they are really holes or openings through regions of stars or nebulous matter.'[3]

In 1902 Dr. Max Wolf of Heidelberg photographed a nebula in Cygnus, and he remarked on a peculiarity of this object; it is 'placed centrally in a very fine lacuna, void of faint stars which surrounds the luminous cloud like a trench. The most striking feature with regard to this object is that the star-void halo encircling the nebula forms the end of a long channel, running eastward from the western nebulous clouds and their lacunae to a length of more than two degrees'. And Wolf proceeded to ask the question: 'Is there a dark mass following the path of the nebula, absorbing the light of the fainter stars? We are far from knowing enough to settle these questions; but one thing we learn anew from

[1] *Lowell Observatory Bulletin*, No. 75.

[2] *Memoir and Correspondence of Caroline Herschel*, p. 269.

[3] *Astronomical Essays*, p. 254.

this interesting nebula, and in a very illustrative manner—that the nebula is geometrically encircled by a ring which is void of faint stars and that this lacuna is the end of a long starless hole. . . . Similar relations seem to exist for all extended nebulae.'[1] These observations of Dr. Wolf were confirmed afterwards by an English astronomer, Mr. W. S. Franks, who referred to the likelihood that some of the nebulae 'are surrounded by dark and relatively cool nebulous matter, which, viewed in its greatest darkness round the edge, is sufficient to absorb and obliterate small stars behind it'.[2]

Independently of Max Wolf, one of America's greatest observers, E. E. Barnard of the Yerkes Observatory, was impressed by the 'vacant regions of the sky' which, he said, 'will before long excite as much study and attention as the nebulae'.[3] At this stage Barnard accepted the current view that most of these dark areas were actually 'holes in the sky'; but he noted certain regions where he felt the received explanation to be unsatisfactory. In regard to a nebulous area in Scorpio he wrote in 1905: 'The blending of this great nebula into the surrounding region where it seems to mingle with the material of the vacancies makes it hard to tell where the nebula leaves off. . . . There is a slight suspicion that certain outlying whirls of this nebulosity have become dark and that they are the cause of the obliteration of the small stars near.'[4] The 'slight suspicions' of 1905 gradually developed into the certainties of 1919. In January of that year Barnard published a catalogue of 182 of these dark markings. By this time he was convinced that these do not represent starless spaces, but are 'really obscuring bodies nearer to us than the distant stars'. 'Their apparent preference for the Milky Way is obviously due to the fact that they are more readily shown with a bright background. They

[1] *Monthly Notices R. A. S.*, lxiv. 839–40. [2] Ib. lxv. 159.
[3] *Popular Astronomy*, xiv. 579. [4] Ib. xiv. 581.

are not, however, strictly confined to the Milky Way.'[1] Many other dark nebulae have been detected. On photographs by Franklin-Adams, 1,550 dark areas have been counted by Lundmark and Melotte. Some of these dark nebulae appear to be comparatively close at hand, and to form part of the local cluster. The obscuring cloud in Taurus is 350 light-years distant; that in Ophiuchus 500 light-years, and that in Orion about 650 light-years away. They appear to be closely connected with and to merge into bright nebulosity. Indeed, bright nebulae seem to be merely regions of those dark clouds which shine either by illumination or excitation. The bright nebula is but a particular case of the dark. In the case of the Orion nebula, H. N. Russell maintains that 'there is no reason to believe that the luminous gas forms the whole or even any large part of the matter present within the region—only that it is selectively sensitive to the incident excitation and therefore gives out most of the light, just as the gases (carbon compounds and nitrogen) do in the coma and tail of a comet'. The Orion nebula, says Russell, is simply a 'superficial fluorescence of a vast dark cloud'.[2] Both in Cepheus and Orion a 'calcium cloud' merges into the nebula and 'in Orion it partly coincides in space with the nebula.'[3]

In 1903 Hartmann of Göttingen detected in the spectrum of the binary star Delta Orionis 'stationary' lines of calcium, which did not show the Doppler effect.[4] In 1923 it was shown by J. S. Plaskett that stationary lines not only of calcium but of sodium occur in the spectra of nearly all stars of types not later than B 3. Plaskett concluded that these lines are produced by absorption in 'a fairly widespread cloud of tenuous material through which the starlight shines without general

[1] *Astrophysical Journal*, xl, p. 12.
[2] *Mount Wilson Communication*, No. 77, p. 4.
[3] O. Struve, *Mount Wilson Contribution*, No. 331, p. 36.
[4] *Astrophysical Journal*, xix, p. 268.

absorption',[1] and the calcium atoms of which are ionized in the vicinity of very hot stars. According to Professor Eddington the evidence points to the existence of a cosmic cloud pervading the Stellar System. 'The system of the stars is floating in an ocean—not merely an ocean of space, not merely an ocean of ether, but an ocean that is so far material that one atom or thereabouts occurs in each cubic inch';[2] and the stationary lines are produced by atoms of calcium which have lost one electron. Otto Struve, a grandson of the famous Otto Struve and great-grandson of the more famous Wilhelm Struve, has concluded from an independent investigation that 'the whole galactic system is immersed in a gaseous substratum consisting of the atoms of various elements'.[3] Dr. Gerasimovič and Dr. Struve find also that the separate atoms of this substratum participate in a rotational movement round a distant central mass in galactic longitude 325°, where so many independent investigations locate the centre of gravity of the Stellar System. Gerasimovič and Struve also suggest that if this interstellar substratum extends throughout all space it is a likely source for the 'hard cosmic radiation' to which the American physicist, Dr. R. A. Millikan, drew attention some years ago, and which seems to demand an extra-terrestrial explanation.

The discovery of dark nebulae and interstellar clouds indicates that space, at least in the vicinity of stars, is by no means so empty as was formerly thought. There is, indeed, evidence that the Solar System is full of diffuse cosmical matter. The solar corona may be a survival of a great irregular nebula surrounding the Sun. Other remnants of bygone ages seem to survive in the comets and meteor streams and in the Zodiacal Light, which appears to be of

[1] *Monthly Notices, R. A. S.*, lxxxiv, p. 90.
[2] *Stars and Atoms*, p. 67.
[3] *Astrophysical Journal*, lxix, p. 33 (*Harvard Reprint*).

vast extent. In 1919 van Rhijn showed that 'at least part of the light of the sky proceeds from a source probably identical with that of the Zodiacal light'—'a kind of Zodiacal light extending over the whole sky'.[1] The Solar System would seem to be enveloped in a ghostly nebulosity, the brighter part of which flashes into visibility during the rare occasion of a total eclipse of the Sun.

Nevertheless, it would seem to be certain that the light of even the most distant stars does not suffer appreciable extinction except in the regions occupied by the dark nebulae proper. Otto Struve finds that a calcium cloud in Cepheus at a distance of 250 parsecs, and which seems to be an outlying portion of the dark nebula, is transparent 'except, of course, for monochromatic radiation'.[2] The work of Shapley on the colours of the stars in the Hercules cluster seems to have settled once for all the question of a general extinction or absorption of light; 'in the direction of the cluster space absorption is entirely negligible'.[3] If there were a general space-absorption, the light of all very distant stars should be tinged with red. But

'it has been possible to measure photographically the colour of stars that are one hundred times as distant as those used in all earlier work, and these distant objects when carefully studied were found to be just as blue as stars of similar spectral class in the solar neighbourhood. It was found, in fact, that pulses of light can travel through interstellar space for two thousand centuries at the speed of 11,000,000 miles a minute without encountering as much light-scattering material as they meet in a thousandth of a second as they pass through the Earth's lower atmosphere.'[4]

While the general transparency of space may therefore be admitted, there can be little doubt that the dense obscuring clouds in the galactic plane are potent factors in modifying

[1] *Mount Wilson Contribution*, No. 173, p. 3.
[2] Ib., No. 331, p. 34.
[3] Ib., No. 116, p. 92.
[4] *Starlight*, pp. 83–4. Shapley has recently shown that space is sensibly transparent for all wave-lengths (*Harvard Bulletin*, No. 864).

the appearance of the Stellar System. The galactic centre in Sagittarius seems to be for ever hidden from the view of the terrestrial observer by dark nebulae of vast extent. More important still, the rifts and coal-sacks in the Milky Way and the great bifurcation running from Cygnus southward are likewise seen to be due to obscuring clouds of cosmical dust. The bifurcation was difficult to account for on any theory of the Universe. In order to explain it Herschel was forced to assume that the stellar disc was cloven in an altogether unnatural way; while the rifts and coal-sacks were so difficult of explanation on the Herschelian theory that Proctor and others were led to abandon the view of the Galaxy as an effect due to star-depth. The discovery of these vast masses of primeval chaos removes the obstacles in the way of a general acceptance of the Herschelian cosmology.

VII

THE GLOBULAR CLUSTERS—SATELLITES OF THE GALAXY

'THIS is but a little patch,' wrote Halley in 1716, 'and similar to the lucid spots round Theta Orionis, in Andromeda and in the Centaur . . . most of them but of few minutes in diameter.'[1] In these words he drew attention to the globular cluster in Hercules, the brightest of its kind visible in northern latitudes. Messier, who used a Newtonian reflector 4 feet long in his sweeps of the heavens, gave Halley's 'little patch' thirteenth place in his catalogue and described it as 'nebuleuse sans étoiles'.[2] Very early in his observing career, William Herschel included this object among those that 'have either plainly appeared to be nothing but stars, or at least to contain stars and to shew every other indication of consisting of them entirely'.[3] In 1787 he described it as 'a most beautiful cluster of stars. It is exceedingly compressed in the middle and very rich. The most compressed part of it is round and is about 2 or 2½′ in diameter; the scattered stars which belong to it extend to 8 or 9′ in diameter but are irregular'.[4] In 1805 he described it as 'a brilliant cluster all resolved into stars',[5] and in 1806 he estimated it to contain at least 14,000 stars.[6]

The Hercules cluster is the most prominent member of that class of clusters described by Herschel as

'certainly the most magnificent objects that can be seen in the heavens. They are totally different from mere groups of stars

[1] *Phil. Trans.*, vol. xxix, p. 392.

[2] *Connaissance des Temps*, 1784, p. 233, quoted by Clerke, *System of the Stars*, p. 239.

[3] *Collected Scientific Papers*, i, p. 158.

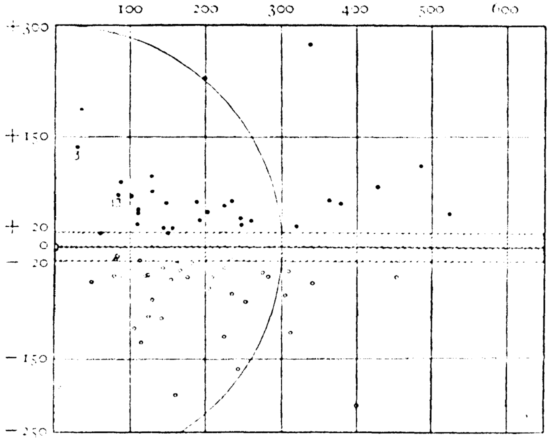
[4] Ib. ii, p. 536. [5] Ib. ii, p. 597. [6] Ib. ii, p. 355.

in their beautiful and artificial arrangement; their form is generally round; and the compression of the stars shews a gradual and a pretty sudden accumulation towards the centre. . . . A centre of attraction is so strongly indicated by all the circumstances of the appearance of the cluster that we cannot doubt a single moment of its existence, either in a state of real solidity or in that of an empty centre, possessed of an hypothetical force, arising from the joint exertion of the numerous stars that enter into the composition of the cluster.'[1]

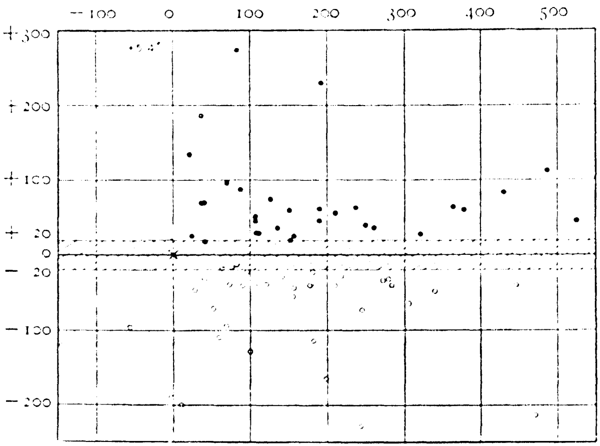
Herschel's observations, then, indicated these clusters to be actual systems, complete by themselves. The 'ripening period of the globular form' he believed in 1814 to imply 'total insulation'.[2] This opinion was expressed at the close of his career, and in the light of his own demonstration of a much greater extension of the Milky Way in its principal plane than he had been disposed to accept in 1785. Sir John Herschel likewise looked on the globular clusters as more or less independent entities. 'We can hardly look upon a group thus insulated . . . as not forming a system of a peculiar and definite character'; and he emphasized, as his father had done, the central condensation, 'not referable to a merely uniform distribution of equidistant stars seen through a globular space'.[3]

One hundred and eleven globular clusters were catalogued by the younger Herschel in 1864. By far the greater number of these were discovered by his father and himself; and since their day very few members of this class have been detected. Indeed, there seems to be evidence that there are still fewer genuine globular clusters than Herschel believed. Dr. S. I. Bailey, one of the leading modern authorities on clusters, puts their number as one hundred, and expresses the view that 'the number now appears to be about complete. It is doubtful whether an increase in the power of telescopes will

[1] *Collected Scientific Papers*, ii, p. 212. [2] Ib. ii, p. 540.
[3] *Outlines of Astronomy*, p. 635.



Distribution of Globular Clusters according to Shapley. The very small semicircle represents region round the Sun containing the brighter stars, corresponding to the 'local cluster'.



Projection of Globular Clusters on plane perpendicular to the Galaxy, according to Shapley, illustrating the symmetrical distribution of clusters and the 'region of avoidance' (position of the Sun indicated by cross).

reveal many new globular clusters'.[1] 'The present lists may be considered essentially complete—a condition that does not prevail for any other important type of celestial object.'[2]

In the latter part of the last century the concept of the One Universe dominated astronomical thought. Proctor formulated the theory of the Milky Way as a zone of comparatively faint stars—intrinsically faint—under the control of the brighter stars. The proof that many of the nebulae were gaseous led to a general modification in the estimates of nebular distances; and as the nebulae were, figuratively speaking, drawn into the main Stellar System, so were the clusters. Proctor was 'wholly disposed to deny' that M 13 and other globular clusters were in any sense external to the main system.[3] In the case of the gaseous nebulae, this led only to a revised estimate of their volumes; in that of the star-clusters to a changed view of the dimensions of the stars composing them. Thus J. E. Gore in 1894 computed the distance of the Hercules cluster at 148 light-years—well within the limits of the Stellar System as then conceived. From this estimated distance he concluded that each of the 2,500 stars of which he assumed the cluster to be composed shines 'with one-sixteenth of the solar light, and if of the same density would have one-sixty-fourth of the Sun's mass. The total mass of the cluster would therefore be equal to about 40 suns. With the data assumed we may therefore conclude that the components of the Hercules cluster are suns of comparatively small size'.[4] Miss Clerke took a similar view of the cluster; taking as a minimum estimate of its distance, which she thought to err on the side of modesty, sixty-five light-years, she found the mass of the entire system to be less than one-third that of the Sun.[5] Little wonder that she asked the question: 'What we cannot but ask ourselves is the true

[1] *Harvard Radio Talks: The Universe of Stars*, p. 173.
[2] Shapley, *Starlight*, p. 115.
[3] *The Universe of Stars*, p. 77.
[4] *The Worlds of Space*, p. 193.
[5] *The System of the Stars*, p. 240.

nature of these mysterious "balls of stars"? Are the luminous particles composing them *suns* in the proper sense?'[1]

Considerable progress was made in the study of globular clusters as a result of the application of photography. Evidently it is a much simpler matter to determine the magnitudes, positions, and, if any, proper motions of cluster stars from plates than from direct observation. Scheiner at Potsdam in 1891 and 1892 drew up the first catalogue of stars in the cluster, containing in all 833 stars. He was followed by Ludendorff, whose catalogue, based on plates taken by the same instrument at Potsdam, but with longer exposures, contained 1,136 stars.[2] These catalogues laid the foundation of our modern knowledge of clusters. Another result of the application of photography was the discovery by the American astronomer Bailey that many globular clusters contained large numbers of variable stars. 128 were found in the southern globular cluster Omega Centauri alone. Variables have been discovered in about thirty globular clusters. The great majority are of short period—about half a day—and in each cluster it is found that what is called the 'median' magnitude—the mean of the maximum and minimum value—is almost exactly the same; whence it is concluded that variables in any particular cluster are of the same absolute magnitude. These variable stars are now grouped with the class of Cepheid variables, and like the 'galactic Cepheids', as those belonging to the Stellar System are called, they obey the period-luminosity law.[3]

Although a great deal of important work on clusters, both practical and theoretical, had been carried through by Scheiner, Ludendorff, von Zeipel, Plummer, Eddington, Jeans, and others, our modern knowledge of their distances

[1] *Problems in Astrophysics*, p. 428.

[2] Ludendorff was not able to detect any traces of proper motions among the individual stars as the result of comparison with Scheiner's plates, taken ten years earlier.

[3] See p. 64.

and their cosmological status is due in the main to Dr. Harlow Shapley, whose important researches into the colours and magnitudes in stellar clusters were commenced in 1914. In a note on 'the purpose of the present study of clusters', Shapley remarked that his object was twofold. Firstly, he sought some advance in knowledge of their internal arrangements and their physical characteristics, and secondly, 'and probably of more importance', he had the idea of making a contribution to the knowledge of our own galactic system.[1] The first cluster to be exhaustively studied was M 13, the great Hercules cluster. By means of the observed colour-indices, Shapley found that the brightest stars, as Sir John Herschel[2] surmised many years before, were of reddish colour; 'in this cluster at least, the giants are brightest when reddest'.[3] Bright blue stars were also found, however, and also a few variables, two at least of which proved to be of the typical Cepheid variety.

Assuming that the brightest stars in M 13 are of equal absolute magnitude with those in the main Stellar System, it is evident that the distance of the cluster can be computed when the apparent magnitudes have been determined—always provided that there is no appreciable absorption of light in space, an assumption which Shapley's study of colour-indices over the whole cluster showed to be without foundation. It would be better, Shapley said, 'if we could assume equality of mean absolute magnitude in a number of stars of the same colour-class in the two systems; or, if we could say, for instance, that the average B-type star has the same intrinsic luminosity wherever found'.[4] However, by taking the mean of values derived from three methods of computing distance—based on variable stars, luminosity-curves, and Russell's data for absolute magnitude respectively

[1] *Mount Wilson Contribution*, No. 115, p. 13.

[2] *Outlines of Astronomy*, p. 638.

[3] Shapley, *Mount Wilson Contribution*, No. 116, p. 65.

[4] Ib., p. 81.

—Shapley found a parallax for the cluster of 0·00003″, corresponding to a distance of 100,000 light-years from the Solar System, and the diameter of the cluster was estimated at 1,100 light-years. The cluster was thus shown to be a vast self-contained organization, containing, according to a photograph by Professor Ritchey with the 60-inch reflector, 30,000 stars brighter than the twenty-first magnitude.[1]

At this stage Shapley accepted the current computations of the extent of the main galactic system, ranging round about 6,000 or 10,000 light-years. The great distance found for M 13 indicated complete independence of our Stellar System; and so Shapley felt justified in saying that 'each globular cluster is a complete and separate system by itself', and that 'some of the globular clusters may be comparable to the galactic system in size, form, or at least, in stellar constituency'.[2] Dr. Shapley and Mr. Francis G. Pease made a close study of the distribution of stars in twelve clusters, including M 13, with the view of ascertaining whether or not these systems were analogous to the galactic system in matter of shape; that is to say, whether their stars were distributed with reference to galactic planes, which 'should reveal themselves through an elliptical distribution of stars'. For nine out of the twelve clusters, five were found to show ellipticity, while three appeared circular and one 'peculiar'. The three clusters with similar density in all directions from the centre are noticeably less condensed, 'a condition that follows naturally if the poles of their galactic planes are assumed to be approximately in the line of sight.'[3] This investigation still further confirmed the theory that star-clusters were independent stellar systems, coequal with the galactic system to which the Sun belongs.

[1] *Star-Clusters and the Structure of the Universe*, p. 14. Thus Herschel's estimate of 14,000 as the minimum number of stars in the cluster was not after all excessive.

[2] *Mount Wilson Contribution*, No. 116, p. 86.

[3] Ib., No. 129, p. 19.

Early in 1917 C. D. Perrine, of the Cordova Observatory, pointed out that the centre of concentration in space of the globular clusters appeared to be almost exactly in the same direction as the dense star-clouds of the Milky Way in Sagittarius and Ophiuchus—a fact emphasized by Hertzsprung in 1912.[1] 'If the distribution of the globular clusters is in fact so closely related to the galaxy . . . it seems improbable that these bodies are strictly "intergalactic".'[2] In the following year Shapley himself came round to this view. His study of the blue stars in the galactic star-clouds had convinced him that the Stellar System was very much more extended in the line of sight than current theories had assumed to be the case. Further, he succeeded in getting parallax measures for sixty-nine globular clusters, a number afterwards augmented to eighty-six, and from the distances deduced from these measures he was able to compute their distribution and dimensions. The methods used for the determination of the distance of M 13 were applied with greater accuracy, but several other and more reliable methods were used, of which the most important was based on the period-luminosity law of the Cepheid variables. Shapley determined from their parallactic motions the mean parallax of eleven Cepheids belonging to the galactic system, and having done this was able, from their apparent magnitudes, to get their absolute magnitudes. He assumed that the absolute magnitudes were dependent on the periods just as in the case of the variables in the small Magellanic Cloud. Having made the reasonable assumption that the period-luminosity law is valid for all Cepheids of both types, he was able to get the parallaxes of 139 galactic Cepheids from their apparent magnitudes, and, what was still more important, to fix the distances of the globular clusters containing Cepheids of either type. For clusters in which no Cepheid

[1] *Observatory*, xl, p. 304; *Astr. Nach.* 4600, p. 265.
[2] *Observatory*, xl, p. 167.

stars had been detected, Shapley used the method of median magnitudes, and a third method, based on a relation between parallaxes and angular diameters.

Applying his more accurate methods, Shapley found that he had over-estimated the distance of M 13. His revised estimate was 36,000 light-years, at which distance 'a star as bright as the Sun would be considerably fainter than the twentieth magnitude'.[1] He found the clusters to range in order of distance from Omega Centauri at 22,000 light-years to N.G.C. 7,006 at 220,000 light-years; but more important still, he discovered a certain symmetry in the distribution of the clusters. It had long been known that the great majority are to be found south of the celestial equator; only about a dozen—and these bright and comparatively close at hand—are located to the north of that line. It used to be thought that these clusters were concentrated to the galactic circle, but Shapley showed that this is not so. 'They are completely missing from the middle part of the galactic belt—scarcely one within five degrees of its central line. Their greatest frequency is some seven or eight degrees from the plane of the Milky Way—a maximum on both sides, but a conspicuous minimum at the galactic circle.'[2] Further, the clusters turned out to be systematically distributed with regard to the Galaxy. He found that of the eighty-six clusters studied, forty-three lie on one side of the galactic plane and forty-three on the other—the clusters forming 'a great roughly defined ellipsoidal system, symmetrically divided by the plane of the Milky Way'.[3] The longest axis of this ellipsoidal system was found to lie in the galactic plane; and the concentration of clusters in the southern hemisphere is seen to be due to the non-central position of the Sun in the main system. It was no longer possible to maintain that globular clusters were independent of the main system, and accordingly

[1] *Star-Clusters and the Structure of the Universe*, p. 18.
[2] Ib., p. 22.
[3] Ib., p. 24.

Shapley was driven to the conclusion that they are dependent sub-systems—'cosmic units' but under the control of the greater galactic system. If the galactic system be likened to a 'continent' the globular clusters are 'small islands' in space; or they may be called the satellite-systems of the Galaxy.

In 1924 and 1925 Shapley was able to get reliable measures of the distances of the two Magellanic Clouds. Hertzsprung in 1913 from a study of its variable stars had estimated the distance of the small Cloud as 30,000 light-years. Shapley by means of the period-luminosity relation found the Cloud to be much more distant—namely, 102,000 light-years. This gives a diameter of 6,500 light-years or 'ten times the distance from the Earth to the Orion nebula'.[1] The Small Cloud seems to be unique in the abnormal brightness of its chief stars, 'the brightest yet recorded somewhat exceeding those of highest luminosity in globular clusters and being more than fifty thousand times as luminous as the Sun';[2] while its brightest variables appear to be giants surpassing Betelgeux or Antares in size—with linear diameters equal to the major axis of Jupiter's orbit. For the Large Cloud Shapley found a distance of 112,000 light-years, so that the Large Cloud would seem to be large in reality and not only in appearance. Its radius is ten times the distance of the Orion nebula. 'Such a cloud centred on the Sun would include the whole local system outlined by the bright class B-stars in Perseus, Orion, Vela, Centaurus, and Scorpio, and extending further would go well beyond Praesepe, the double cluster in Perseus and many of the other open clusters in the Milky Way.'[3] The Clouds seem to be at the same order of distance as the clusters, but they are systems of a different type.

Shapley in 1918 essayed a provisional hypothesis as to the relation of the clusters to the main galactic system. The outstanding fact about the real distribution of the clusters is their

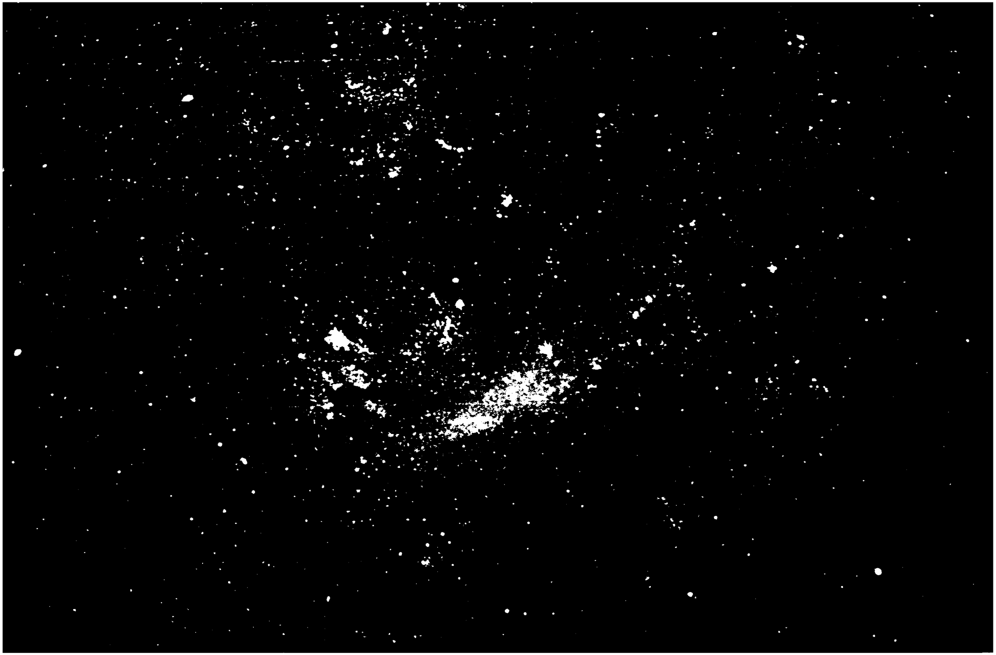
[1] *The Magellanic Clouds* (Harvard reprint from *Scientia*, 1925), p. 76.
[2] *Harvard Circular*, No. 255, p. 5. [3] Ib., No. 268, p. 3.

concentration to two belts on either side of the Milky Way and their avoidance of the galactic plane. It may, of course, be maintained that this avoidance is apparent only, due to the dark obscuring clouds which lie all along the plane. But this will hardly explain the fact that not a single cluster is to be found in the mid-galactic region. So he concluded that the mid-galactic segment is actually a region of avoidance on the part of clusters; and for this avoidance there must be some cosmological reason.

Dr. V. M. Slipher of the Lowell Observatory showed in 1917 that globular clusters as a whole have negative radial velocities;[1] that is to say, these great stellar systems are nearing the Sun with large velocities, which means that they are approaching the galactic system. This suggested to Shapley that globular clusters will be absorbed in the main system. Hence the region of avoidance is more than a region of avoidance, but rather 'a region of attraction and demolition'.[2] When a globular cluster enters the segment it ceases to be a globular cluster. It is absorbed into the main system. Support is accorded to this view by the fact that the clusters nearest to the plane are the least condensed; they would seem to be breaking up under the gravitational pull of the galactic system. On this theory the numerous sub-organizations, such as the open clusters and moving star-groups which are intermingled with the general star-fields of the Galaxy may have at one time been globular clusters thus absorbed. As Shapley remarks, if a cluster were thus absorbed two results should follow.

'Faint stars in globular clusters are of small mass and of more than average velocity and in their orbital motions frequently attain great distances from the centre. When the globular cluster approaches a disturbing body as massive as the general galactic system, such stars are of course most readily lost and intermingled

[1] *Popular Astronomy*, xxvi, p. 8.
[2] *Mount Wilson Contribution*, No. 157, p. 11.



The Nebecula Major or Large Magellanic Cloud

with galactic stars. On the other hand, the massive cluster stars which are mostly of high luminosity, having low peculiar velocities, and maintaining in their sub-system a high degree of stability, retain their organization longer in a disrupting field, and except for rare and accidental encounters with galactic stars, undergo as a single unit the general perturbations of the galactic system.'[1]

They become 'moving clusters' in the main system. But while the comparatively small globular clusters would be simply merged in the galactic system, large systems such as the Magellanic Clouds might be able to pass through the equatorial segment, though with considerable difficulty. It is significant that both the Clouds are receding from the galactic system. 'Assuming that the velocity of recession has been essentially the same in the past,' wrote Shapley in 1924, 'we find that the small Magellanic Cloud was in or near the plane of the Milky Way in the year—$1{\cdot}9 \times 10^8$.[2] It was then possibly indistinguishable from the clouds existing there at the present time.'[3]

Granted the truth of Shapley's cosmogonic hypothesis, the local cluster of which the Sun is a member may have at one time in the remote past formed part of a globular cluster which was absorbed ages ago by the general system; and the galactic system as we know it may have had its origin in the intermingling of two clusters and may have grown to its present dimensions by absorbing other clusters. Thus, in Herschel's cosmology, the Stellar System was viewed as breaking up under the influence of the 'clustering power' into subordinate systems; while in Shapley's cosmology the main system has been formed by the union of smaller systems and is destined to grow enormously with the passage of the ages.

It is evident that the scale of the Universe adopted by Shapley is altogether dependent on the validity of his methods

[1] *Mount Wilson Contribution*, No. 157, p. 14.
[2] Or 190,000,000 years ago.
[3] *Harvard Circular*, No. 255, p. 4.

of determining stellar distances, and chiefly on the assumptions that the brightest stars in globular clusters on the average have the same luminosity as those in the galactic system, and that cluster Cepheids and galactic Cepheids are strictly comparable. Both of these assumptions have been contested by several competent authorities. Thus Dr. Curtis of Allegheny, Pennsylvania, contended in 1921 that the B-type stars 'furnish something of a dilemma in any attempt to utilize them to determine cluster distances'.[1] 'There may exist', he said, 'B-type stars of only two to five times the brightness of the Sun.'[2] In regard to the Cepheid variables, Curtis concluded Shapley's assumption of the existence of a period-luminosity relation for galactic Cepheids to be unwarranted, and that entire confidence cannot be placed on the hypothesis that Cepheids and cluster-type variables are always super-giant stars. Accordingly, Curtis rejected Shapley's great distances, both inter-galactic and extra-galactic. 'Our galaxy is probably not more than 30,000 light-years in diameter and perhaps 5,000 light-years in thickness';[3] and he gave as his estimate for the distance of the Hercules cluster 8,000 light-years.[4] Shapley pointed out in reply the extreme improbability of believing that the nearer B-stars are giants and those at great distances dwarfs;[5] and regarding the Cepheids he remarked that it would be possible to discard these stars altogether, 'use instead either the red giant stars and spectroscopic methods, or the hundreds of B-type stars upon which the most capable stellar astronomers have worked for years and derive much the same distance for the Hercules cluster and for other clusters and obtain consequently similar dimensions for the galactic system'.[6] The distances derived by these methods, Shapley rightly pointed out,

[1] *The Scale of the Universe, Bulletin of National Research Council*, vol. 2, part 3 (1921), p. 209.

[2] Ib., p. 210. [3] Ib., p. 198. [4] Ib., p. 210. [5] Ib., p. 184.

[6] Ib., pp. 187–8.

afford strong evidence for the reliability of the assumptions and methods involved in the Cepheid method.

Shortly before his death, Dr. Kapteyn, in collaboration with Dr. van Rhijn, investigated fourteen faint galactic Cepheids of the so-called cluster type assumed by Shapley to be giants, and found them to have a large annual proper motion. From these, by Kapteyn's method of computing mean parallaxes, they deduced large parallaxes and relative proximity, with consequent low luminosity for the particular Cepheids. If this were so, these Cepheids would be dwarfs; and they concluded, therefore, that the similar stars in clusters might also be dwarfs. If such were the case, Shapley's distances for the clusters would be eight times too great.[1] Shapley pointed out, however, that long-period Cepheids were known to exist in five bright globular clusters. 'Four of these clusters, Messier 3, 5, 15 and Omega Centauri, contain also large numbers of cluster type variables, and the difference in the magnitude between the two types is in all cases very close to the difference predicted by the adopted period-luminosity curve. . . . It seems hardly reasonable to accept Kapteyn and van Rhijn's suggestion that the long-period Cepheids in all these clusters are abnormally faint.'[2] Shapley also pointed out that the 'cluster variables as a class have high spatial velocity, and therefore that the large proper motions are not incompatible with high velocity', and contended that 'the procedure involving parallactic motion, used by Kapteyn and van Rhijn to get the mean distances of cluster variables, is inappropriate for stars of high peculiar velocity'.[3] The method of getting average parallaxes from parallactic motions for groups of stars is valid when large numbers of stars are concerned; but it breaks down when applied to special classes of stars whose peculiar velocities may be greater than the average. There is reason to believe

[1] *Bulletin of Astronomical Institutes of the Netherlands*, No. 8.
[2] *Harvard Circular*, No. 237, p. 5. [3] Ib., p. 2.

that variables and kindred stars have large peculiar velocities. Sanford demonstrated in 1921 that stars of class R have abnormally high velocities,[1] and Shapley has shown that long-period giant variables are likewise fast-moving bodies.[2] There appears to be a theoretical reason for the high velocity in the case of cluster-variables.

'The average velocity of globular clusters', says Shapley, 'is comparable with that of cluster variables in the galactic system. This may indicate that many of the cluster variables were originally members of the same extra-galactic cluster or cloud. It is possible that the high velocity and variability of these stars both arise from close encounters with bodies of excessive mass, which would occur more frequently in the centres of globular clusters than anywhere else in the stellar system.'[3]

In 1923 Mr. R. E. Wilson of Albany Observatory, New York, discussed all the data available for 84 Cepheids, including the stars of the cluster type investigated by Kapteyn and van Rhijn. Mr. Wilson, after a careful study of the proper motions of these Cepheids, found no evidence of a probable correction of more than 40 per cent. to Shapley's parallaxes of either the short or the long period Cepheids.[4] But according to Kapteyn himself, a systematic correction ought to be applied to the proper motions of these stars. 'This would give a net reduction of approximately 20 per cent.,' says Wilson, but 'in view of the uncertainties on the peculiar motions of the short-period stars and the lack of determination in the suggested systematic corrections to the proper

[1] *Mount Wilson Annual Report*, 1921, p. 268.

[2] *Harvard Circular*, No. 237, p. 2.

[3] Ib., p. 10.

[4] Mr. Peter Doig informs me that 'the modern trigonometrical parallaxes of sixteen Cepheids, although very small, are probably sufficiently accurate to compare with the period-luminosity values used by Shapley. When this is done the average trigonometrical value for these sixteen is found to be 45 per cent. higher than Shapley's, thus supporting Wilson's result' (cf. *Observatory*, l, pp. 221–22).

motions, it seems that the most probable factorial correction to Shapley's parallaxes must be nearer to 1·4 than to 1·0.'[1] In 1927 Oort concluded from an investigation of the radial velocities of Cepheids that 'Shapley's parallaxes for long-period Cepheids are nearly correct'.[2]

But perhaps the most important piece of confirmatory evidence in favour of Shapley's distances for the clusters is afforded by Lindblad's work on the effect of absolute magnitude on spectra. He discovered that a certain portion of the continuous spectrum is less intense in stars of low luminosity than in those of great intrinsic brightness;[3] and he found on a certain plate of the Hercules cluster that 'three of the brightest stars were sufficiently well separated from each other to permit an examination of their spectra. The examination showed the stars to be giants of spectral type Ko. 'This agrees with the degree of luminosity found by Shapley if the stars are pseudo-Cepheids; if they are ordinary giants we should estimate the absolute magnitude around +1.'[4]

That the brightest stars in the cluster are actually giants would seem, therefore, to have been put beyond reasonable doubt by Lindblad's investigation. On the whole the balance of evidence is in favour of the legitimacy of Shapley's assumption that galactic Cepheids of both classes are comparable with cluster Cepheids, and that therefore his distances for the clusters by the Cepheids method are fair approximations to the truth. Their weight is increased by the fact that they are confirmed by other methods of measurement. Shapley's cosmology in its main outlines holds the field at the present time.

[1] *Astronomical Journal*, vol. xxxv (1923), p. 43.
[2] *Bulletin of Astronomical Institutes of the Netherlands*, iv, no. 133.
[3] *Mount Wilson Annual Report*, 1921, p. 271.
[4] *Mount Wilson Contribution*, No. 228, p. 12.

VIII

ISLAND UNIVERSES

THAT the so-called nebulae fall into several distinct classes was suspected by Herschel, and became more and more evident with the progress of astronomy. Early spectroscopic observations indicated a marked difference between the extended nebulae such as that in Orion and the more regular types such as that in Andromeda. Recent research, as we have seen, has fully established the fact that galactic and extra-galactic nebulae are generically distinct. The extra-galactic nebulae are divided by Hubble into the spiral and globular classes.

The most sensational discovery of the great six-foot mirror of the Rosse reflector was that of the spiral form of a number of the nebulae. In April 1845 the nebula M 51 in Canes Venatici, visible in Sir John Herschel's telescope as a split ring, was seen in the Rosse mirror to present the appearance of what has been aptly called 'a vast whirlpool of light'.[1] By 1850, fourteen nebulae had been definitely recognized as of spiral form. But notwithstanding the fact that Lord Rosse's telescope was unrivalled in light-grasping power, the discovery of spiral nebulae was received with a good deal of incredulity. It was not until the advent of photography that the objective existence of the spirals was placed beyond all doubt. The pioneering work in nebular photography of A. A. Common and Isaac Roberts in England and of J. E. Keeler in America finally confirmed the discovery of Lord Rosse.

These photographic surveys indicated that the nebulae were a great deal more numerous than they had been supposed to be. Dr. Max Wolf at Heidelberg picked them up in scores, and his photographs registered not only large

[1] Clerke, *History of Astronomy in the Nineteenth Century*, p. 147.

numbers of nebulae all over the sky but nebulae in groups and clusters.[1] Keeler carried through with the Crossley reflector of the Lick Observatory a photographic survey of the heavens, the result of which was the discovery of great numbers of faint nebulae hitherto unrecorded. He concluded indeed that 120,000 nebulae were within reach of his great reflector and that a very large proportion of these were of the spiral form.

In keeping with later nineteenth-century cosmological thought all nebulae were viewed as primeval world-stuff, and despite the continuous nature of their spectra the spiral nebulae of which the Andromeda nebula was recognized to be the largest and brightest were regarded as solar or stellar systems in the making. The famous photograph of the Andromeda nebula secured by Dr. Isaac Roberts in December 1888 was hailed as a pictorial representation of the past of our system.

'This wonderful photograph,' wrote J. E. Gore, 'which will mark an epoch in astronomical research, shows us this great nebula for the first time in a clearly intelligible form and calls to mind the nebular theory of Laplace, in which the planets of the Solar System are supposed to have been evolved from rings detached from a rotating nebulous mass.'[2]

And Sir Robert Ball declared in 1901 that

'if Kant had never lived, if Laplace had never announced his nebular theory, if the discoveries of Sir William Herschel had not been made, I still venture to think that a due consideration of the remarkable photograph of the famous great spiral[3] . . . would have suggested the high probability of that doctrine which we describe as the nebular theory. If an artist thoroughly versed in the great facts of astronomy had been commissioned to represent the nebular origin of our system as perfectly as a highly cultivated yet disciplined imagination would permit, I do not think that he

[1] See biography of Max Wolf in my *Astronomers of To-day*.
[2] *The Worlds of Space*, p. 199. [3] M 51.

could have designed anything which could answer the purposes more perfectly than does that picture which is now before us.'[1]

Chamberlin and Moulton, in their 'planetesimal hypothesis' of the origin of the Solar System, took the spiral as the type from which the system had in their opinion been evolved; and Sir James Jeans, in his later theorizing on stellar origins, likewise made the spiral nebula—assumed to be gaseous—his starting-point.

Spectroscopic evidence had of course suggested some essential difference between the irregular nebulae and the spirals. But it was generally assumed that they were true nebulae, in a later stage of evolution than those which show unmistakable gaseous spectra. Of the Andromeda nebula, Miss Clerke wrote: 'That it is still in the plastic state there can be little doubt';[2] and this was the prevailing view, though it should be said that Vogel had emphasized the fact that the continuous spectrum of the typical nebula of this kind presented precisely the appearance of the spectrum of a star-cluster,[3] and that his assistant Scheiner secured in January 1899 a spectrogram of the Andromeda nebula which in his opinion proved the nebula to be a cluster of sun-like stars.[4] Further, the information collected during the early years of the century raised genuine doubts as to whether the spirals could be classified as nebulae at all. Astronomers had long been familiar with certain peculiarities in the distribution of nebulae. The two Herschels and Proctor had drawn attention to the fact that in certain regions of the sky, not far from the galactic poles, nebulae were very numerous; and the German astronomer d'Arrest in 1872 had pointed out that while most of the nebulae were situated at great distances from the Milky Way, these nebulae known to be gaseous

[1] *The Earth's Beginning*, pp. 193–4.
[2] *The System of the Stars* (2nd ed.), p. 261.
[3] Scheiner, *Astronomical Spectroscopy* (trans. by Frost), p. 232.
[4] *Photographie de Gestirne*, p. 332, quoted by Clerke, ib., p. 260.

showed a strong galactic concentration—twenty-five out of thirty-two nebulae known to him lying in the galactic zone.[1] Irregular nebulae, too, were seen to be intermingled with B-type stars, and planetary nebulae to be connected with Wolf-Rayet stars; but the spirals betrayed no affinities to either of these stellar classes. But the strongest proof of an essential difference was found when the radial motions of a sufficiently large number of nebulae of both classes had been measured. Keeler in 1890 found the Orion nebula to be moving very slowly, cosmically speaking; and this is true of diffuse nebulae as a class.

In 1912 Dr. V. M. Slipher, now director of the Lowell Observatory at Flagstaff, as a result of his pioneer work on the radial velocities of the spirals, announced that the great Andromeda nebula was moving towards the Solar System with a speed of 200 km. per second. In 1914 he published values of radial velocity for fourteen spirals, all but two of which were receding with enormous velocities. 'The average velocity of the spirals', Slipher stated, 'is about twenty-five times the average stellar velocity.'[2] In 1921 he announced that two spirals—N.G.C. 584 and N.G.C. 936—were receding with the 'unparalleled velocities' of 1800 and 1300 km. per second.[3] These great speeds afforded strong evidence of a generic difference between the two main classes of nebulae.

In 1905 Miss Clerke, one of the most careful and impartial of astronomers, expressed the view that 'the question whether nebulae are external galaxies hardly any longer needs discussion. It has been answered by the process of research. No compotent thinker with the whole of the available evidence before him can now, it is safe to say, maintain any single nebula to be a star-system of co-ordinate rank with the Milky Way'.[4] Yet within six years the tide of astronomical

[1] Scheiner, *Astronomical Spectroscopy*, p. 233.

[2] *Popular Astronomy*, xxiii, p. 23.

[3] *Lowell Observatory Observation Circular*, Jan. 17, 1921.

[4] *The System of the Stars* (2nd ed.), p. 349.

opinion set strongly in the direction of the view that the spiral nebulae are external galaxies. In 1911 the late Prof. Frank W. Very, an able American astronomer, wrote a paper entitled, 'On the White Nebular Galaxies'.[1] The title was suggestive, and the object of the article was to show, after a discussion of the dimensions of the galactic system, that the spirals cannot be intergalactic objects, and must therefore be island universes; and he computed the distance of the apparently smallest and faintest of these nebulae at a million light-years. In 1914 Eddington adopted Very's theory. 'The island universe theory', he said, 'is to be preferred as a working hypothesis; and its consequences are so helpful as to suggest a distinct probability of its truth.'[2] The spiral form of the nebulae, used by Ball at the beginning of the century as an argument for the nebular hypothesis, now began to suggest analogies with the greater galactic system. That the Stellar System is in reality spiral in form has been suggested from time to time. The Dutch astronomer Easton put forward the idea that the galactic clouds form a spiral system and that the whole Galaxy is a double-armed spiral; and Eddington showed that if this were so, the analogy between our Stellar System and the spiral nebulae would be very close. He laid a special emphasis on the two arms of the typical spiral nebula. These, he said,

'have an interesting meaning for us in connexion with stellar movements.... Either matter is flowing into the nucleus from the spiral branches, or it is flowing out from the nucleus into the branches.... We have currents of matter in opposite directions at the points where the arms merge in the central aggregation.... Here then we have an explanation of the prevalence of motions to and fro in a particular straight line; it is the line from which the spiral branches start out. The two star-streams and the double-branched spirals arise from the same cause.'[3]

[1] *Astr. Nach.*, 4536.

[2] *Stellar Movements and the Structure of the Universe*, p. 243.

[3] Ib., pp. 244–5.

From 1916 onwards a considerable amount of knowledge was gained concerning the spiral nebulae, but much of that knowledge tended to weaken the 'island universe' theory. Shapley showed the galactic system to be many times larger than had hitherto been supposed, and the globular clusters to be not independent stellar systems, as he had surmised in the initial stages of his work, but certainly dependants of the Galaxy. More important still, Dr. Adriaan van Maanen, the distinguished Dutch astronomer, who for a number of years devoted himself to the study of the spiral nebulae by means of the Mount Wilson 60-inch reflector, obtained for several spiral nebulae fairly large parallaxes, indicating these nebulae to be much closer at hand than the island universe theory would allow. In the case of two of these spirals (N.G.C. 224 and 5194) Dr. van Maanen admitted that his parallaxes were 'larger than most astronomers will like to accept', for 'although the exposures show images of the central parts of these two spirals which are fairly measurable, it seems that the diffuseness of their images as compared with those of the comparison stars may easily have introduced a systematic error of the order of the parallaxes themselves'.[1]

In 1916 van Maanen announced that he had been able to secure 'preliminary evidence' of internal motion in the spiral M 101. By careful comparison of photographs by means of the stereo-comparator, he found that numerous points in the nebula had an appreciable motion—78 points moving to the left and 9 to the right, 58 moving outward and 28 inward. The measures indicated 'a small but scarcely reliable decrease of rotational motion with increasing distance from the centre'.[2] Evidence was later adduced by van Maanen for internal motions in the case of M 81, M 51, and M 33, in general along the spiral arms; and believing these motions to be real, he strongly emphasized their incompatibility with

[1] *Mount Wilson Contribution*, No. 158, p. 7.
[2] *Mount Wilson Communication*, No. 29, p. 4.

the island universe theory.[1] If M 33, for instance, were a Galaxy comparable to ours, its distance must be of the order of a million or more light-years, and the motions would represent velocities greater than the velocity of light. His measures were corroborated by Lampland at the Lowell Observatory and by Kostinsky, a Russian astronomer, though Lundmark found a velocity of rotation only one-tenth of that found by van Maanen. On the whole, however, van Maanen's results gained general acceptance, and the island universe theory was regarded as seriously weakened.

Shapley in 1919 adduced further unfavourable evidence. Comparing the luminosity of novae in the Stellar System with novae in the spirals, he concluded that if the spirals were external universes their novae would attain an absolute magnitude 200,000 times as bright as the novae of our own system.

> 'An upper limit to the intrinsic brightness attainable by stars is suggested by recent observational and theoretical work and this limit is much fainter than −16. . . . The luminosity of about 2,000 stars of the solar environs is now known and probably none is even a ten-thousandth part as luminous as absolute magnitude −16. Hence stellar luminosities of this order seem out of the question and accordingly the close comparability of the spirals containing such novae to our galaxy appears inadmissible.'[2]

Shapley also enumerated facts at variance with the island universe theory—the avoidance by the spirals of low galactic latitudes, their irregular concentration to the galactic poles, and the systematic relation of their radial velocities to the galactic system.[3]

Accordingly, he placed the spirals definitely within the Stellar System at an average distance of 20,000 light-years[4]—less than that of the globular clusters. He was accordingly

[1] *Mount Wilson Communication*, No. 72, p. 5.
[2] *Pub. Astr. Soc. Pacific*, October 1919, p. 11.
[3] Ib., p. 7. [4] Ib., p. 11.

The Great Spiral Nebula (M 51)

obliged to assume the non-stellar nature of the spirals. His suggested interpretation required that 'two types of sidereal organization prevail generally throughout extra-galactic space; spiral nebulae, and stars of known types assembled for the most part into globular clusters'. Spirals as a class are receding with great velocities—if the shifts of their spectral lines are really Doppler effects—while globular clusters are approaching the galactic system, so the hypothesis demanded 'that gravitation be the ruling power of stars and star-clusters, and that a repulsive force, radiation pressure or an equivalent, predominate in the resultant behaviour of spiral nebulae'. The evidence suggested 'that the galactic system now moves as a whole through space, driving the spiral nebulae before it and absorbing and disintegrating isolated stellar groups'.[1] This theory was admittedly based, however, on the assumption that the spectral displacements of the spirals are really due to radial motions of recession. But according to De Sitter the shift towards the red end of the spectrum is a relativity effect, due to the slowing down of atomic vibrations at great distances;[2] and this view has met with a considerable degree of acceptance.

Shapley threw out as a tentative suggestion the idea that the spirals represent the failure to form stars from the original nebulosity owing to the presence of too much material. On this theory the spirals consist of the unused material driven away towards the galactic poles by radiation-pressure from the stars, and would be analogous to the cometic and meteoric matter in the Solar System. This is not out of harmony with the view expressed by T. J. J. See that 'if repulsive forces are everywhere at work expelling dust from the stars for the formation of nebulae it is evident that as it is repelled by the stars it will tend to gather, especially in vacant regions or spaces remote from the stars,

[1] *Mount Wilson Contribution*, No. 161, p. 27.
[2] *Monthly Notices*, *R. A. S.* lxxviii, p. 26.

and should accumulate with maximum density near the poles of the Milky Way'.[1] H. D. Curtis, in controversy with Shapley, put up a very strong case in 1921 in favour of the island universe theory;[2] but the trend of opinion seemed to be definitely towards an interpretation of the spirals as truly nebulous. Dr. Jeans at this stage based his cosmogony upon the spirals. In the case of M 101, whose distance was computed by van Maanen at 5,000 light-years, Jeans stated that this nebula was breaking up into stars—the stars being generated at the rate of one every few hundred years. Shapley pointed out in 1924 that this hypothesis was in direct opposition to observation. Were spirals generating stellar clusters or typical stars larger and less dense than the Sun, there should be many giant stars in the vicinity of the spirals. This, he found, was not the case.[3]

Rather unexpectedly the island universe theory was rehabilitated in 1925 by observational evidence of a convincing kind which seems to indicate that van Maanen's suspicion of a systematic error in his parallaxes was well founded, and that his measures of internal motion were likewise vitiated by a similar error. Hubble announced that with the 100-inch Mount Wilson reflector he had succeeded in partially resolving into stars two of the brightest spirals—M 31 (the Andromeda nebula) and M 33. He likewise detected Cepheids in both of these nebulae and in N.G.C. 6822, and as the period-luminosity relationship was found to hold in each nebula, Hubble was able to determine the distances of these nebulae as 230,000 parsecs in the case of N.G.C. 6822 and 285,000 parsecs, or round about 900,000 light-years, in the case of M 31 and M 33.[4] In the case of N.G.C. 6822, a faint object somewhat similar to the Magellanic Clouds,

[1] *Popular Astronomy*, xix, p. 618.
[2] *Bulletin National Research Council*, vol. 2, part 3, No. 11.
[3] *Harvard Circular*, No. 257.
[4] *Mount Wilson Annual Report*, 1925, p. 106.

originally discovered by Barnard in 1883, Shapley had in 1923 reached an estimate of its distance slightly greater than, but in general accord with, that of Hubble. From a calculation based on its brightest stars, visible to us as of the eighteenth magnitude, Shapley computed its distance to be a million light-years and concluded it to be a great star-cloud, 'at least three or four times away as the most distant of known globular clusters and probably quite beyond the limits of the galactic system'.[1] N.G.C. 6822 would appear to be the nearest independent system. The Magellanic Clouds, it is true, are very similar in practically every respect[2] to our galactic system. The two Clouds and N.G.C. 6822 have been called by Dr. Willem J. Luyten 'universes in vest-pocket edition', but where the Clouds differ from N.G.C. 6822 and still more from M 33 and M 31 is that they are situated at distances comparable to those of the globular clusters and are therefore controlled to a greater or lesser extent by the main galactic system.[3]

Hubble's preliminary results have been abundantly confirmed by his own later work. He found M 33 to be 'an extremely distant system of stars and nebulae similar in many respects to the Magellanic Clouds'. It differs from the Clouds, however, in that 'there is a symmetrical arrangement of material with respect to a dominating nucleus. Detailed study of the stars within the limits of observation—the three or four brightest magnitudes—indicates that they are normal giants such as are known in other systems'.[4] Hubble points

[1] *Harvard Bulletin*, No. 796.

[2] Except that no temporary star has ever been seen in either cloud (W. J. Luyten, *Island Universes, Harvard Reprint* from *Natural History*, xxvi, p. 389).

[3] Hubble, however, thinks the clouds are 'most readily interpreted as irregular non-galactic nebulae' (*Mount Wilson Contribution*, No. 320, p. 34), but Luyten thinks that 'though somewhat vagrant and "cometary" in behaviour' they are 'permanent members of the galaxy' (*Harvard Reprint* from *Proc. Nat. Acad. Sciences*, xiv, p. 244). Oort thinks it possible that 'the clouds are satellites of the galactic system' (*Bulletin of Astronomical Institutes of the Netherlands*, iv, p. 132).

[4] *Mount Wilson Contribution*, No. 310, p. 38.

out, however, and in this Shapley agrees with him, that M 33 is much smaller than our Galaxy, while M 31 occupies an intermediate position. None of the extra-galactic objects yet investigated is as large as our Stellar System.[1] 'So far', says Luyten, 'we have struck only real "island" universes: a continent as large as our own we have yet to find.'[2]

Hubble's values for the distances of the spirals were in the main confirmed by Öpik of Tartu (Dorpat) and Lundmark, who likewise removed one of the chief objections to the island universe theory—that based on the luminosity of galactic novae. Lundmark showed that galactic novae at maximum are among the brightest known stars in the galactic system, brighter than had hitherto been believed; he showed also that the novae in spirals are not very dissimilar to them. In the galactic system the recorded novae have been strongly concentrated to the Sagittarius region, by common consent the centre of the system where the stars are most densely crowded and there is much obscuring material.

'The novae in our stellar system, although confined to the galactic regions, are not found in the star-clouds but at the borders of the Milky Way or in relation to the bright and dark nebulae. It may have some significance that the Andromeda novae prefer that side of the nebula where the absorption is rather marked.... In some cases they have also appeared in small dark "rifts" of the nebula.'[3]

[1] A possible close analogy between the galactic system and the Andromeda Galaxy (M 31) has been pointed out by Mr. Peter Doig. M 31 has two companion nebulae which, if physically connected with it, would seem to be related to it in the same way in which the Magellanic Clouds are related to the galactic system. 'A further point of similarity, which might be expected,' says Mr. Doig, 'is, however, not found. Our Milky Way system if seen from a distance of 700,000 light-years, would have about seventy globular clusters disposed around it, which would appear as hazy stars of the thirteenth magnitude on photographs with a large reflector. There is no indication that such objects are found round the spirals Messier 31 and Messier 33' (*An Outline of Stellar Astronomy*, pp. 154–5).

[2] *Island Universes* (reprint), p. 390.

[3] *Monthly Notices*, lxxxv, p. 884–5.

The Spiral Nebula M 33 Trianguli

In 1926 Shapley succeeded in getting good values for the distance of a cluster of 103 spiral nebulae in the constellations Coma and Virgo. Using the known angular diameters, integrated magnitudes and colour-indices of these spirals, he found the distance of the group to be ten million light-years. This is in good agreement with the value of eight million light-years obtained by Lundmark for one member of the group, N.G.C. 4486.[1] This cluster would seem to be a physically connected group of spirals, 'a cloud of galaxies', Shapley calls it, 'with diameter of about one-fifth of its distance from the Sun'.[2] This cluster of external systems may be regarded as, to a certain extent, analogous to our own galactic system and its dependent sub-systems.

Hubble has followed up his work on the nearer spirals with a general investigation of extra-galactic nebulae as a class. That such nebulae are exceedingly numerous has, of course, been known since the time of Keeler's photographic survey. Hubble finds that 300,000 nebulae are likely to be visible on fast plates in the 60-inch reflector and these 'appear to be the inhabitants of space out to a distance of the order of $2{\cdot}4 \times 10^7$ parsecs'. He further concludes that the 100-inch reflector with long exposures under good conditions will probably reach the total visual magnitude 18·0. This represents 'a distance of the order of $4{\cdot}4 \times 10^7$ parsecs, or 140 million light-years, within which it is expected that about two million nebulae will be found'.[3] It is by no means improbable that many systems larger than our galactic system exist among the two million.

The status of our system among the two million is that of a large spiral, the product probably of the union of a number of smaller systems. Seares clearly states the place of our system in these words:

'The galactic system is a vast organization resembling M 33,

[1] *Monthly Notices*, lxxxv, p. 888. [2] *Harvard Circular*, No. 294, p. 1.
[3] *Mount Wilson Contribution*, No. 324, p. 46.

although probably larger and perhaps even more completely resolved into stars. It includes a central condensation, scattered stars, and aggregations of stars distributed over the galactic plane; the large groups of the Milky Way correspond to the knots and condensations of the spiral arms of the nebula. An outlying aggregation of exceptional size and density but having the physical characteristics of condensations in the nebular arms in that it includes giant stars of high temperature accounts for the local cluster. Like the spirals, the system also includes diffuse nebulous material concentrated near the galactic plane, dark and obscuring, or luminous if stimulated to shine by the radiation of neighbouring stars of high temperature.'[1]

Despite the vast distances between each of the two million spirals, including our system, they can hardly be altogether independent of each other. Strömberg's researches on stellar motion indicate a definite connexion between the galactic system and the system of spiral nebulae.[2] Charlier and Lundmark both conclude that the Stellar System and the spiral nebulae form together what the eighteenth-century thinker Lambert called a system of the 'second order'[3]—the Stellar System being viewed as a system of the 'first order'. 'Whether galaxies of the third order exist', says Lundmark, 'we do not know.'[4]

According to the theory of relativity, the universe is 'finite yet unbounded'. Dr. Albert Einstein of Berlin and his co-worker, Dr. Willem De Sitter of Leyden, have computed the possible size of the Universe from the mean density of the matter of space. They found its radius to be 10^{13} times the distance of the Earth from the Sun; if this be correct, a ray of light would take 1,000 million years to go 'round the

[1] *Mount Wilson Contribution*, No. 347, pp. 53–4.

[2] Ib., No. 275, pp. 23–4.

[3] If we take the Earth-Moon System, however, as a typical system of the first order and the Solar System as a typical system of the second, the local cluster as of the third, and the Stellar System as of the fourth, this fifth system may be called a system of the fifth order.

[4] *Monthly Notices, R. A. S.* lxxxv, p. 893.

world'.[1] Hubble finds much greater dimensions for the Universe, the 'radius of curvature' being 600 times 140 million light-years. Admitting the truth of the theory of relativity, the frontiers of the known Universe will have to be advanced 600 times their present distance before man can claim to have surveyed the whole of what we may call the finite and unbounded Universe. Indeed, we have travelled far in four centuries. In 1529 the world was homely and comprehensible to a degree—a central Earth for the benefit of whose inhabitants the whole of the Universe had been constructed, with Sun, Moon, and stars moving round it to minister to their needs. The Universe of 1929, even if finite, extends to 600 times 140 million times six billion miles! Certainly if this is finitude, it is a kind of finitude which bludgeons the mind into stupefaction.

But even if the space we know in association with matter—the space of which the radius of curvature is $2{\cdot}7 \times 10^{10}$ parsecs—is finite, can we venture to say that it exhausts the whole of reality? Here we enter into metaphysical regions that are beyond our depth, but may not this 'finite' Universe be but a part, indeed, a transient manifestation of the All? There may be more than mere poetry in Shelley's fine words in his 'Ode to Heaven':

> What is Heaven? A globe of dew,
> Filling, in the morning new,
> Some eyed flower whose young leaves waken
> On an unimagined world:
> Constellated and unshaken,
> Orbits measureless, are furled
> In that frail and fading sphere,
> With ten millions gathered there,
> To tremble, gleam and disappear.[2]

[1] Eddington, *Space, Time, and Gravitation*, p. 161.

[2] *Complete Poetical Works of Percy Bysshe Shelley* (Hutchinson's ed.), p. 572.

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